
MISSILE
TECHNOLOGY
CONTROL
REGIME
(MTCR)
ANNEX HANDBOOK
2017

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Introduction

The Missile Technology Control Regime (MTCR)

Introduction – The Missile Technology Control Regime (MTCR)

- Argentina
- Australia
- Austria
- Belgium
- Bulgaria
- Brazil
- Canada
- Czech Republic
- Denmark
- Finland
- France
- Germany
- Greece
- Hungary
- Iceland
- India
- Ireland
- Italy
- Japan
- Luxembourg
- Netherlands
- New Zealand
- Norway
- Poland
- Portugal
- Republic of Korea
- Russian Federation
- South Africa
- Spain
- Sweden
- Switzerland
- Turkey
- Ukraine
- United Kingdom
- United States

MTCR Partners



The Missile Technology Control Regime is an informal and voluntary association of countries which share the goals of non-proliferation of systems capable of delivering weapons of mass destruction (other than manned aircraft), and which seek to coordinate national export licensing efforts aimed at preventing their proliferation. The MTCR was originally established in 1987 by Canada, France, Germany, Italy, Japan, the United Kingdom and the United States. Since that time, the number of MTCR partners has increased to a total of 35 countries, all of which have equal standing within the regime.

The MTCR was initiated partly in response to the increasing proliferation of weapons of mass destruction (WMD), and in particular nuclear, chemical, and biological weapons. The risk of proliferation of WMD is well recognized as a threat to international peace and security, including by the UN Security Council in its Summit Meeting Declaration of January 31, 1992. While concern has traditionally focused on state proliferators, after the tragic events of 11 September 2001, it became evident that more also has to be done to decrease the risk of WMD delivery systems falling into the hands of terrorist groups and individuals. One way to counter this threat is to maintain vigilance over the transfer of missile equipment, material, and related technologies usable for systems capable of delivering WMD.

The MTCR rests on adherence to common export policy guidelines (the MTCR Guidelines) applied to an integral common list of controlled items (the MTCR Equipment, Software and Technology Annex). The MTCR does not take export licensing decisions as a group. Rather, individual partners are responsible for implementing the Guidelines and Annex on the basis of sovereign national discretion and in accordance with national legislation and practice.

All MTCR decisions are taken by consensus, and MTCR partners regularly exchange information about relevant national export licensing issues in the context of the Regime's overall aims. A Plenary Meeting is held annually and chaired on a rotational basis. Recent plenary sessions have been held in Copenhagen, Denmark (2006); Athens, Greece (2007); Canberra, Australia (2008); Rio de Janeiro, Brazil (2009); Buenos Aires, Argentina (2011); Berlin Germany (2012); Rome, Italy (2013); Oslo, Norway

(2014); Rotterdam, Netherlands (2015), and Busan, Republic of Korea (2016). In addition, inter-sessional consultations take place monthly through Point of Contact (POC) meetings in Paris, while Technical Experts Meetings, Information Exchanges, and Enforcement Experts Meetings are held on an ad hoc basis. The MTCR has no secretariat; distribution of the Regime's working papers is carried out through the POC, the functions of which are performed by the Ministry of Foreign Affairs of France.

The MTCR Equipment, Software and Technology Annex

The MTCR Equipment, Software and Technology Annex is the Regime's list of controlled items – both military and dual-use – including virtually all key equipment, materials, software, and technology needed for the development, production, and operation of systems capable of delivering WMD. The annex is divided into "Category I" and "Category II" items. Partner countries exercise restraint in the consideration of all transfers of items contained in the annex, and all such transfers are considered on a case-by-case basis. The annex is updated periodically to improve its clarity and take into account evolving technologies.

Greatest restraint is applied to what are known as Category I items. These items include complete rocket systems (including ballistic missiles, space launch vehicles and sounding rockets) and unmanned aerial vehicle systems (including cruise missiles systems, target and reconnaissance drones) with capabilities exceeding a 300 km/500 kg range/payload threshold; production facilities for such systems; and major sub-systems including rocket stages, re-entry vehicles, rocket engines, guidance systems and warhead mechanisms.

The remainder of the annex is regarded as Category II, which includes complete rocket systems (including ballistic missiles systems, space launch vehicles and sounding rockets) and unmanned aerial vehicles (including cruise missile systems, target drones, and reconnaissance drones) not covered in Item I, capable of a maximum range equal to or greater than, 300 km. Also included are a wide range of equipment, material, and technologies, most of which have uses other than for systems capable of delivering WMD. While still agreeing to exercise restraint, partners have greater flexibility in the treatment of Category II transfer applications.

The MTCR Annex Handbook

This annex handbook is designed to assist in implementing export controls on MTCR Annex items. It explains what MTCR-controlled equipment and technologies are, how they are used, how they work, what other uses they may have, and what they look like. The annex covers an extremely broad range of items, and the handbook emphasizes only those technologies most critical to delivery system design and production. The handbook is based on the MTCR Annex in force on October 20, 2016. The most current version of the MTCR Annex can be accessed via the MTCR website at www.mtcr.info.

The handbook is organized like the MTCR Annex, by item and subitem. Each section follows the same format: the actual MTCR Annex text is re-produced in a highlighted section, followed by a detailed elaboration and images. Any MTCR Annex "Notes" relevant to a particular subitem have been included with the actual text to facilitate easier reading. Each subitem is discussed separately. When reviewing subitems, the reader should pay attention to the header text in the item, which may contain additional descriptors for each subitem. Where applicable, side boxes identifying countries that can produce or export particular subitems accompany the highlighted text. This list of countries that might be producing the specific technologies or systems under individual items is representative and not necessarily exhaustive.

The MTCR Annex Handbook is produced by the United States Government for the purpose of facilitating effective export controls on MTCR-controlled items. Unlike the MTCR Guidelines and Annex, the Handbook is not an official MTCR publication of record. The images, websites, and other references in this handbook are intended to give examples of material and equipment with features similar to those that the MTCR Annex describes. It is important to note that presence of certain items or equipment in a photograph, on a website, or in a reference does not, necessarily, mean that the pictured or referenced item meets the MTCR control specifications. Decisions on the control status of an item are made by considering the technical specifications of a specific product on a case-by-case basis.

Appendix I

The Missile Technology Control Regime (MTCR) Guidelines

Appendix I – The Missile Technology Control Regime (MTCR) Guidelines for Sensitive Missile-Relevant Transfers

1. The purpose of these Guidelines is to limit the risks of proliferation of weapons of mass destruction (i.e. nuclear, chemical and biological weapons), by controlling transfers that could make a contribution to delivery systems (other than manned aircraft) for such weapons. The Guidelines are also intended to limit the risk of controlled items and their technology falling into the hands of terrorist groups and individuals. The Guidelines are not designed to impede national space programs or international cooperation in such programs as long as such programs could not contribute to delivery systems for weapons of mass destruction. These Guidelines, including the attached Annex, form the basis for controlling transfers to any destination beyond the Government's jurisdiction or control of all delivery systems (other than manned aircraft) capable of delivering weapons of mass destruction, and of equipment and technology relevant to missiles whose performance in terms of payload and range exceeds stated parameters. Restraint will be exercised in the consideration of all transfers of items within the Annex and all such transfers will be considered on a case-by-case basis. The Government will implement the Guidelines in accordance with national legislation.

2. The Annex consists of two categories of items, which term includes equipment and technology. Category I items, all of which are in Annex items 1 and 2, are those items of greatest sensitivity. If a Category I item is included in a system, that system will also be considered as Category I, except when the incorporated item cannot be separated, removed or duplicated. Particular restraint will be exercised in the consideration of Category I transfers regardless of their purpose, and there will be a strong presumption to deny such transfers. Particular restraint will also be exercised in the consideration of transfers of any items in the Annex, or of any missiles (whether or not in the Annex), if the Government judges, on the basis of all available, persuasive information, evaluated according to factors including those in paragraph 3, that they are intended to be used for the delivery of weapons of mass destruction, and there will be a strong presumption to deny such transfers. Until further notice, the transfer of Category I production facilities will not be authorised. The transfer of other Category I items will be authorised only on rare occasions and where the Government (A) obtains binding government-to-government undertakings embodying the assurances from the recipient government called for in paragraph 5 of these Guidelines and (B) assumes responsibility for taking all steps necessary to ensure that the item is put only to its stated end-use. It is understood that the decision to transfer remains the sole and sovereign judgement of the Government.

3. In the evaluation of transfer applications for Annex items, the following factors will be taken into account:

A. Concerns about the proliferation of weapons of mass destruction;
B. The capabilities and objectives of the missile and space programs of the recipient state;
C. The significance of the transfer in terms of the potential development of delivery systems (other than manned aircraft) for weapons of mass destruction;
D. The assessment of the end use of the transfers, including the relevant assurances of the recipient states referred to in sub paragraphs 5.A and 5.B below;
E. The applicability of relevant multilateral agreements.
F. The risk of controlled items falling into the hands of terrorist groups and individuals.

4. The transfer of design and production technology directly associated with any items in the Annex will be subject to as great a degree of scrutiny and control as will the equipment itself, to the extent permitted by national legislation.

5. Where the transfer could contribute to a delivery system for weapons of mass destruction, the Government will authorise transfers of items in the Annex only on receipt of appropriate assurances from the government of the recipient state that:

A. The items will be used only for the purpose stated and that such use will not be modified nor the items modified or replicated without the prior consent of the Government;
B. Neither the items nor replicas nor derivatives thereof will be retransferred without the consent of the Government.

6. In furtherance of the effective operation of the Guidelines, the Government will, as necessary and appropriate, exchange relevant information with other governments applying the same Guidelines.

7. The Government will:

A. provide that its national export controls require an authorisation for the transfer of non-listed items if the exporter has been informed by the competent authorities of the Government that the items may be intended, in their entirety or part, for use in connection with delivery systems for weapons of mass destruction other than manned aircraft;
B. and, if the exporter is aware that non-listed items are intended to contribute to such activities, in their entirety or part, provide, to the extent compatible with national export controls, for notification by the exporter to the authorities referred to above, which will decide whether or not it is appropriate to make the export concerned subject to authorisation.

8. The adherence of all States to these Guidelines in the interest of international peace and security would be welcome.

Appendix II

Units, Constants, Acronyms and Abbreviations

Appendix II – Units, Constants, Acronyms and Abbreviations Used in this Annex

ABEC	Annular Bearing Engineering Committee
ABMA	American Bearing Manufacturers Association
ANSI	American National Standards Institute
Angstrom	1 x 10^{-10} metre
ASTM	American Society for Testing and Materials
bar	unit of pressure
^{0}C	degree Celsius
cc	cubic centimetre
CAS	Chemical Abstracts Service
CEP	Circle of Equal Probability
dB	decibel
g	gram; also, acceleration due to gravity
GHz	gigahertz
GNSS	Global Navigation Satellite System e.g. ‘Galileo’ ‘GLONASS’ – Global’naya Navigatsionnaya Sputnikovaya Sistema ‘GPS’ – Global Positioning System
h	hour
Hz	hertz
HTPB	Hydroxyl-Terminated Polybutadiene
ICAO	International Civil Aviation Organisation
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
ISO	International Organization for Standardization
J	joule
JIS	Japanese Industrial Standard
K	Kelvin
kg	kilogram
kHz	kilohertz
km	kilometre
kN	kilonewton
kPa	kilopascal
kW	kilowatt
m	metre
MeV	million electron volt or mega electron volt
MHz	megahertz
Milligal	10^{-5} m/s^2 (also called mGal, mgal or milligalileo)
mm	millimetre
mm Hg	mm of mercury
MPa	megapascal
mrad	milliradian
ms	millisecond
µm	micrometre

N	newton
Pa	pascal
ppm	parts per million
rads (Si)	radiation absorbed dose
RF	radio frequency
rms	root mean square
rpm	revolutions per minute
RV	Re-entry Vehicles
s	second
Tg	glass transition termperature
Tyler	Tyler mesh size, or Tyler standard sieve series
UAV	Unmanned Aerial Vehicle
UV	Ultra violet

Appendix III
Table of Conversions

Appendix III – Table of Conversions

Table of Conversions used in this Annex		
Unit (from)	Unit (to)	Conversion
bar	pascal (Pa)	1 bar = 100 kPa
g (gravity)	m/s^2	1 g = 9.806 65 m/s^2
mrad (millirad)	degrees (angle)	1 mrad ≈ 0.0573°
rads	ergs/gram of Si	1 rad (Si) = 100 ergs/gram of silicon (= 0.01 gray [Gy])
Tyler 250 mesh	mm	for a Tyler 250 mesh, mesh opening 0.063 mm

Addendum

Statement of Understanding

Addendum – Statement of Understanding

Statement of Understanding

Members agree that, in those cases where the term "national equivalents" are specifically allowed as alternatives to specified International Standards, the technical methods and parameters embodied in the national equivalent would ensure that the requirements of the standard set by the specified International Standards are met.

MTCR Annex

Introduction, Definitions and Terminology

MTCR Annex – Introduction, Definitions and Terminology

1. Introduction

(a) This Annex consists of two categories of items, which term includes equipment, materials, "software" or "technology". Category I items, all of which are in Annex Items 1 and 2, are those items of greatest sensitivity. If a Category I item is included in a system, that system will also be considered as Category I, except when the incorporated item cannot be separated, removed or duplicated. Category II items are those items in the Annex not designated Category I.

(b) In reviewing the proposed applications for transfers of complete rocket and unmanned aerial vehicle systems described in Items 1 and 19, and of equipment, materials, "software" or "technology" which is listed in the Technical Annex, for potential use in such systems, the Government will take account of the ability to trade off "range" and "payload".

(c) General Technology Note:
The transfer of "technology" directly associated with any goods controlled in the Annex is controlled according to the provisions in each Item to the extent permitted by national legislation. The approval of any Annex item for export also authorises the export to the same end-user of the minimum "technology" required for the installation, operation, maintenance, and repair of the item.

Note:

Controls do not apply to "technology" "in the public domain" or to "basic scientific research".

(d) General Software Note:
The Annex does not control "software" which is either:
1. Generally available to the public by being:
    a. Sold from stock at retail selling points without restriction, by means of:
        1. Over-the-counter transactions;
        2. Mail order transactions; or
        3. Electronic transactions; or
        4. Telephone call transactions; and
    b. Designed for installation by the user without further substantial support by the supplier; or
2. "In the public domain".

Note:

The General Software Note only applies to general purpose, mass market "software".

(e) <u>General Minimum Software Note:</u>

The approval of any Annex item for export also authorises the export, or transfer, to the same end user of the minimum “software”, excluding source code, required for the installation, operation, maintenance or repair of the item in order to ensure the item’s safe operation as originally intended.

<u>Note:</u>

The General Minimum Software Note also authorises export of “software” intended to correct defects (bug fixes) in a previously legally exported item, provided that the capability and/or performance of the item are not otherwise enhanced.

(f) <u>Chemical Abstracts Service (CAS) Numbers:</u>

In some instances chemicals are listed by name and CAS number. Chemicals of the same structural formula (including hydrates) are controlled regardless of name or CAS number. CAS numbers are shown to assist in identifying whether a particular chemical or mixture is controlled, irrespective of nomenclature. CAS numbers cannot be used as unique identifiers because some forms of the listed chemical have different CAS numbers, and mixtures containing a listed chemical may also have different CAS numbers.

2. Definitions

For the purpose of this Annex, the following definitions apply:

"Accuracy"
Usually measured in terms of inaccuracy, means the maximum deviation, positive or negative, of an indicated value from an accepted standard or true value.

"Basic scientific research"
Experimental or theoretical work undertaken principally to acquire new knowledge of the fundamental principles of phenomena or observable facts, not primarily directed towards a specific practical aim or objective.

"Development"
Is related to all phases prior to "production" such as:

- design
- design research
- design analysis
- design concepts
- assembly and testing of prototypes
- pilot production schemes
- design data
- process of transforming design data into a product
- configuration design
- integration design
- layouts

"In the public domain"
This means "software" or "technology" which has been made available without restrictions upon its further dissemination. (Copyright restrictions do not remove "software" or "technology" from being "in the public domain".)

"Microcircuit"
A device in which a number of passive and/or active elements are considered as indivisibly associated on or within a continuous structure to perform the function of a circuit.

"Microprograms"
A sequence of elementary instructions maintained in a special storage, the execution of which is initiated by the introduction of its reference instruction register.

"Payload"
The total mass that can be carried or delivered by the specified rocket system or unmanned aerial vehicle (UAV) system that is not used to maintain flight.

Note:

The particular equipment, subsystems, or components to be included in the "payload" depends on the type and configuration of the vehicle under consideration.

Technical Notes:

1. Ballistic Missiles

a. "Payload" for systems with separating re-entry vehicles (RVs) includes:
- *1. The RVs, including:*
  - *a. Dedicated guidance, navigation, and control equipment;*
  - *b. Dedicated countermeasures equipment;*
- *2. Munitions of any type (e.g. explosive or non-explosive);*
- *3. Supporting structures and deployment mechanisms for the munitions (e.g. hardware used to attach to, or separate the RV from, the bus/post-boost vehicle) that can be removed without violating the structural integrity of the vehicle;*
- *4. Mechanisms and devices for safing, arming, fuzing or firing;*
- *5. Any other countermeasures equipment (e.g. decoys, jammers or chaff dispensers) that separate from the RV bus/post-boost vehicle;*
- *6. The bus/post-boost vehicle or attitude control/velocity trim module not including systems/subsystems essential to the operation of the other stages.*

b. "Payload" for systems with non-separating re-entry vehicles includes:
- *1. Munitions of any type (e.g. explosive or non-explosive);*
- *2. Supporting structures and deployment mechanisms for the munitions that can be removed without violating the structural integrity of the vehicle;*
- *3. Mechanisms and devices for safing, arming, fuzing or firing;*
- *4. Any countermeasures equipment (e.g. decoys, jammers or chaff dispensers) that can be removed without violating the structural integrity of the vehicle.*

2. Space Launch Vehicles

"Payload" includes:

- *a. Spacecraft (single or multiple), including satellites;*
- *b. Spacecraft-to-launch vehicle adapters including, if applicable, apogee/perigee kick motors or similar manoeuvering systems and separation systems.*

3. Sounding Rockets

"Payload" includes:

- *a. Equipment required for a mission, such as data gathering, recording or transmitting devices for mission-specific data;*
- *b. Recovery equipment (e.g. parachutes) that can be removed without violating the structural integrity of the vehicle.*

4. Cruise Missiles

"Payload" includes:

a. Munitions of any type (e.g. explosive or non-explosive);
b. Supporting structures and deployment mechanisms for the munitions that can be removed without violating the structural integrity of the vehicle;
c. Mechanisms and devices for safing, arming, fuzing or firing;
d. Countermeasures equipment (e.g. decoys, jammers or chaff dispensers) that can be removed without violating the structural integrity of the vehicle;
e. Signature alteration equipment that can be removed without violating the structural integrity of the vehicle.

5. Other UAVs

"Payload" includes:

a. Munitions of any type (e.g. explosive or non-explosive);
b. Mechanisms and devices for safing, arming, fuzing or firing;
c. Countermeasures equipment (e.g. decoys, jammers or chaff dispensers) that can be removed without violating the structural integrity of the vehicle;
d. Signature alteration equipment that can be removed without violating the structural integrity of the vehicle;
e. Equipment required for a mission such as data gathering, recording or transmitting devices for mission-specific data and supporting structures that can be removed without violating the structural integrity of the vehicle;
f. Recovery equipment (e.g. parachutes) that can be removed without violating the structural integrity of the vehicle;
g. Munitions supporting structures and deployment mechanisms that can be removed without violating the structural integrity of the vehicle.

"Production"
Means all production phases such as:
- production engineering
- manufacture
- integration
- assembly (mounting)
- inspection
- testing
- quality assurance

"Production equipment"
Means tooling, templates, jigs, mandrels, moulds, dies, fixtures, alignment mechanisms, test equipment, other machinery and components therefor, limited to those specially designed or modified for "development" or for one or more phases of "production".

"Production facilities"
Means “production equipment” and specially designed "software" therefor integrated into installations for "development" or for one or more phases of "production".

"Programs"
A sequence of instructions to carry out a process in, or convertible into, a form executable by an electronic computer.

"Radiation hardened"
Means that the component or equipment is designed or rated to withstand radiation levels which meet or exceed a total irradiation dose of 5×10^5 rads (Si).

"Range"
The maximum distance that the specified rocket system or unmanned aerial vehicle (UAV) system is capable of travelling in the mode of stable flight as measured by the projection of its trajectory over the surface of the Earth.

Technical Notes:

1. *The maximum capability based on the design characteristics of the system, when fully loaded with fuel or propellant, will be taken into consideration in determining "range".*
2. *The "range" for both rocket systems and UAV systems will be determined independently of any external factors such as operational restrictions, limitations imposed by telemetry, data links or other external constraints.*
3. *For rocket systems, the "range" will be determined using the trajectory that maximises "range", assuming ICAO standard atmosphere with zero wind.*
4. *For UAV systems, the "range" will be determined for a one-way distance using the most fuel-efficient flight profile (e.g. cruise speed and altitude), assuming ICAO standard atmosphere with zero wind.*

"Software"
A collection of one or more "programs", or "microprograms", fixed in any tangible medium of expression.

"Technology"
Means specific information which is required for the "development", "production" or "use" of a product. The information may take the form of "technical data" or "technical assistance".

"Technical assistance"
May take forms such as:
- instruction
- skills
- training
- working knowledge
- consulting services

"Technical data"

May take forms such as:

- blueprints
- plans
- diagrams
- models
- formulae
- engineering designs and specifications
- manuals and instructions written or recorded on other media or devices such as:
  - disk
  - tape
  - read-only memories

"Use"

Means:

- operation
- installation (including on-site installation)
- maintenance
- repair
- overhaul
- refurbishing

3. Terminology

Where the following terms appear in the text, they are to be understood according to the explanations below:

(a) "Specially designed" describes equipment, parts, components, materials or "software" which, as a result of "development", have unique properties that distinguish them for certain predetermined purposes. For example, a piece of equipment that is "specially designed" for use in a missile will only be considered so if it has no other function or use. Similarly, a piece of manufacturing equipment that is "specially designed" to produce a certain type of component will only be considered such if it is not capable of producing other types of components.

(b) "Designed or modified" describes equipment, parts or components which, as a result of "development", or modification, have specified properties that make them fit for a particular application. "Designed or modified" equipment, parts, components or "software" can be used for other applications. For example, a titanium coated pump designed for a missile may be used with corrosive fluids other than propellants.

(c) "Usable in", "usable for", "usable as" or "capable of" describes equipment, parts, components, materials or "software" which are suitable for a particular purpose. There is no need for the equipment, parts, components or "software" to have been configured, modified or specified for the particular purpose. For example, any military specification memory circuit would be "capable of" operation in a guidance system.

(d) "Modified" in the context of "software" describes "software" which has been intentionally changed such that it has properties that make it fit for specified purposes or applications. Its properties may also make it suitable for purposes or applications other than those for which it was "modified".

Category I - Item 1
Complete Delivery Systems

Category I – Item 1: Complete Delivery Systems

1.A. Equipment, Assemblies and Components

1.A.1. Complete rocket systems (including ballistic missiles, space launch vehicles, and sounding rockets) capable of delivering at least a 500 kg "payload" to a "range" of at least 300 km.

- Brazil
- Canada
- China
- Egypt
- France
- Germany
- India
- Iran
- Israel
- Italy
- Japan
- North Korea
- Pakistan
- Russian Federation
- South Korea
- Spain
- Syria
- Ukraine
- United Kingdom
- United States

Global Production



Nature and Purpose: Complete rocket systems are self-contained missiles and launch vehicles which carry both fuel and oxidizer internally and accelerate their payloads to high velocity. After propellants are expended ("burnout"), the payload for many systems continues on a predominantly unpowered, ballistic trajectory either into orbit or to a target on earth. Depending on its range and trajectory, a rocket may or may not leave the atmosphere.

Complete rocket systems usually consist of four elements: (1) the payload or warhead; (2) one or more propulsion subsystems to accelerate the payload to the required velocity; (3) a guidance and control system, which navigates and steers the rocket vehicle along a planned trajectory to a pre-determined destination (not all rockets are guided, however); and (4) structural elements that hold everything together.

Evaluation of systems covered under this Item must take into account the ability to trade off payload and range. The inherent capability of a missile may differ significantly from manufacturers' specifications or intended operational concept. For example, a space launch vehicle specified to deliver small satellites (less than 500 kg) to orbit might be capable of sending more than 500 kg to distances greater than 300 km, exceeding the control criteria.

Method of Operation: Rocket propulsion works by expelling onboard matter in the direction opposite to the desired missile motion (conservation of momentum). High performance for speed and distance is achieved when the exhaust is expelled at a high speed and the remaining part of the missile has a low mass compared to the total mass expelled. High exhaust speeds are correlated with high temperature combustion of the propellants. The latter may be either solid, liquid, or a hybrid of the two, inside the missile, while in all cases the exhaust consists of hot gases. Achieving a low mass for the remaining parts

of the missile requires weight minimizing techniques such as utilizing lightweight engines and efficient structures made from high-strength materials.

Complete rocket systems and subsystems are checked for operational readiness prior to launch, and the flight plan or trajectory is programmed into an onboard guidance computer, which controls and steers the rocket in order to maintain the correct trajectory. The total flight time, re-entry speed and range of rocket systems can be manipulated by altering the planned trajectory.

Ballistic missiles have three main flight phases: the 'boost phase' or 'ascent phase'; the 'mid-course phase'; and the 'terminal phase'. During the boost phase, liquid or solid propellants generate thrust to launch the missile and accelerate it to a maximum velocity. Longer range missiles generally have multiple stages: each stage terminates its thrust when its fuel is expended or no longer needed and is separated from the rest of the rocket, and the next stage is ignited.



Figure 1: The launch of a space launch vehicle. (ULA – Carleton Bailie)

For those ballistic missiles that leave the atmosphere, during the 'mid-course phase', the missile is coasting after boost to the point of re-entry into the atmosphere. In the initial part of this phase, the missile will continue to increase in altitude up to the apogee (farthest point from earth). If the missile is carrying multiple warheads, they are usually released or ejected during this phase. Some warheads might not be ejected until shortly before the missile re-enters the atmosphere, and in some cases, the payload remains attached to the missile body as it re-enters the atmosphere.

If the warhead separates from the missile body, then it will be carried within a Re-entry Vehicle (RV). The RV will be carried within a payload assembly, which may include multiple warheads and RVs. On missiles equipped with Multiple Independently-targeted Re-entry Vehicles (MIRVs), the RVs will be carried by a post-boost vehicle, which has its own propulsion capability so that it can move in space and deploy each RV against its own designated target.

The 'terminal phase' refers to the part of the trajectory after the missile or warheads have re-entered the atmosphere (below 120 km altitude).

It should be noted that while some systems may have listed payload and/or range thresholds that fall beneath the minimum 300 km and 500 kg requirements for this category, it is possible to sacrifice payload for increased range or range for increased payload. Range and payload adjustments might be accomplished by increasing or decreasing the amount of propellants carried or via other modifications. Such changes may lead to the item in question falling outside the manufacturer's specifications or intended operational concept.

Typical Missile-Related Uses: Space launch vehicles and sounding rockets are used to place satellites in orbit or to gather scientific data in the upper atmosphere, respectively. The critical differences between these systems and offensive ballistic missiles are their payloads and intended use. With the addition of a weapons payload and different guidance algorithms, space launch vehicles and sounding rockets can be used as ballistic missiles. In fact, many space launch vehicles have been developed from, and share components with, ballistic missiles.

Several operational ballistic missiles have been used as space launch vehicles. Sounding rockets, like ballistic missiles, do not reach orbit, but their guidance algorithms and trajectories may be very different, in the absence of a particular downrange target.

Other Uses: N/A

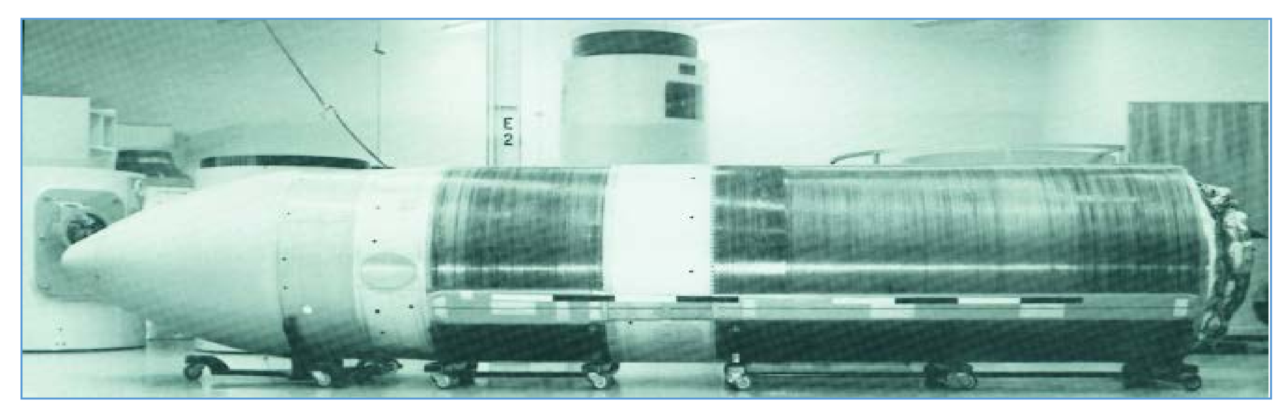


Figure 2: A solid propellant, submarine launched ballistic missile. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

Appearance (as manufactured): Complete rocket systems are large, long, narrow cylinders. When assembled, these systems typically have dimensions of at least 8 m in length, 0.8 m in diameter, and 5,000 kg in weight, with a full load of propellant. Some representative photos of ballistic missile systems and space launch vehicles are shown in Figures 1, 2 and 3. Submarine launched ballistic missiles (SLBMs) may be relatively wide and short to fit within a submarine (Figure 2). A sounding rocket is shown in Item 19.A.1., as sounding rockets are typically smaller than missiles controlled by Item 1.A.1.

Figure 4 provides an expanded view of a notional ballistic missile, showing a range of MTCR-controlled items. In order to illustrate different types of rockets, the first stage is shown with solid propellant and the second stage has liquid propellants.

The forward end, or nose, typically has a conical, elliptical, or bulbous fairing that houses the payload, and joins to the cylindrical body in which the propellants are located. The blunt aft end is straight, flared, or symmetrically finned for stability during launch and atmospheric flight. The body of the rocket system houses the rocket motor(s) for solid propellants, or tanks and engines for liquid propellants. The rocket system surface is usually made of metallic or composite materials with heat-absorbing materials or protective coatings. Depending on their intended use, some surfaces may be unfinished (not painted or otherwise coated).

Appearance (as packaged): A complete rocket system is seldom packaged as a fully assembled unit for shipment from the manufacturer to its point of use or storage. Instead, the major subsystems (stages) are shipped in crates or sealed metal containers to an assembly facility near the launch location, where they are assembled, tested for their operational readiness, and erected for vertical launch. Final assembly is sometimes completed with the missile in a horizontal position, while some missiles are assembled by stacking the stages vertically.

Exceptions include mobile ballistic missiles, which can be transported fully assembled to the launch location after storage in a horizontal position on a wheeled vehicle. Such a vehicle may be a mobile erector launcher (MEL, a trailer linked to a towing vehicle) or a transporter-erector-launcher (TEL, a long vehicle with its own engine and drivetrain). A MEL or a TEL has a mechanism for tilting the missile upwards before launching. Mobile missiles are likely to be contained inside a canister such that the missile itself is not exposed until ready for launch.





Figure 3: ***Left:*** **A Space Launch Vehicle (ISRO).** ***Right:*** **Road Mobile SS-25, a solid propellant, single warhead intercontinental ballistic missile (ICBM). (Maxim Shipenkov/AFP/Getty Images)**

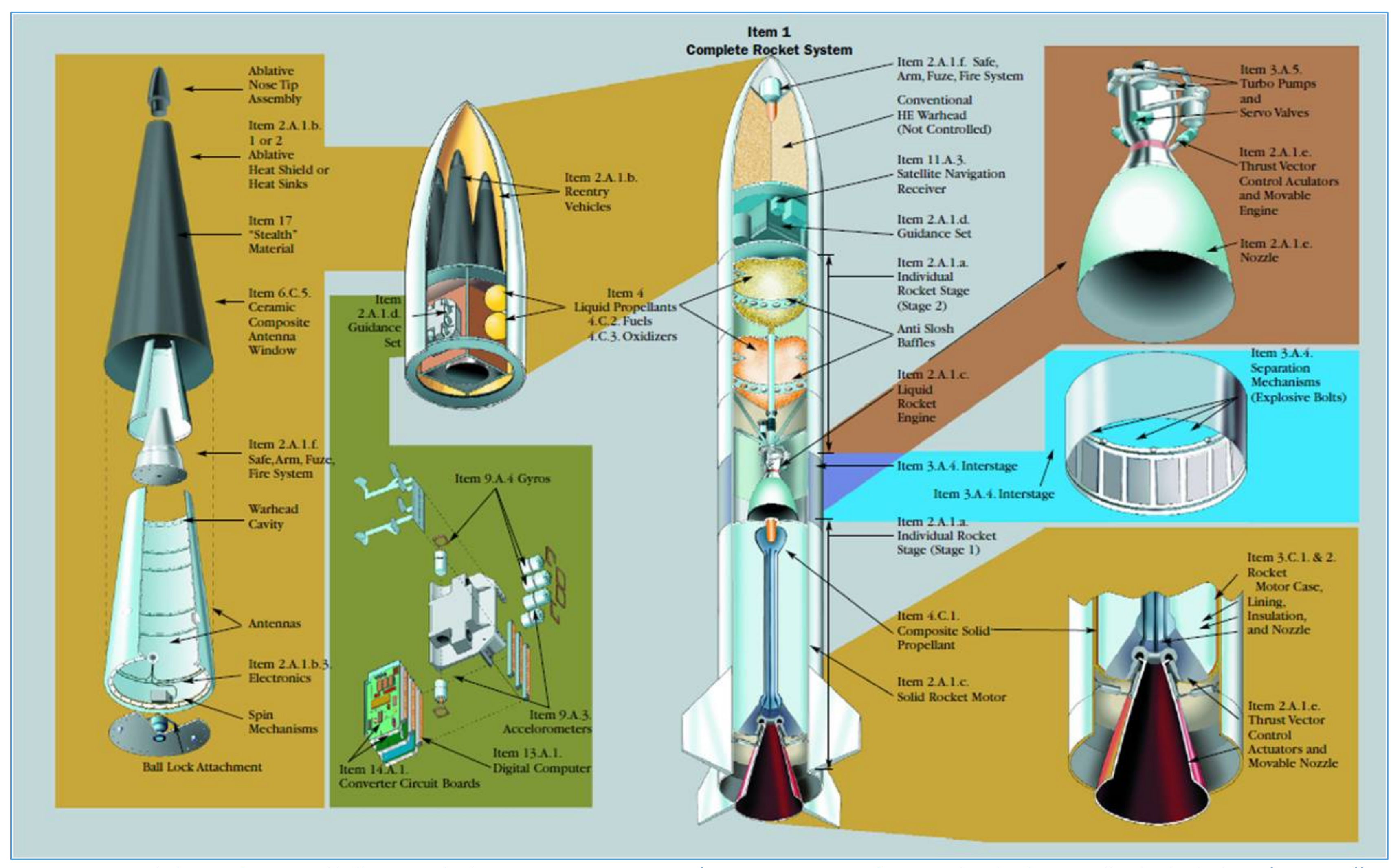


Figure 4: Expanded view of a notional ballistic missile showing MTCR Annex items. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

1.A.2. Complete unmanned aerial vehicle systems (including cruise missiles, target drones and reconnaissance drones) capable of delivering at least a 500 kg "payload" to a "range" of at least 300 km.

- Australia
- China
- France
- Germany
- Israel
- Pakistan
- Russian Federation
- United States

Global Production



Nature and Purpose: Unmanned aerial vehicle (UAV) systems are typically air-breathing vehicles which use aerodynamic lift to fly (and thereby perform their entire mission within the earth's atmosphere). UAVs are usually powered by small turbine or piston engines that drive either free or ducted propellers, or small jet engines (some of these propulsion systems are covered by Item 3 of the MTCR Annex). Cruise missiles typically operate at high subsonic speeds (less than 900 km/hr), while other UAVs tend to fly at speeds between 360 km/hr to 640 km/hr.

Evaluation of systems covered under this Item must take into account the ability to trade off payload and range. This inherent capability may differ significantly from manufacturers' specifications or intended operational concept.

Several of the UAV systems covered in this section of the MTCR are large systems capable of operating at altitudes of about 20,000 m, have flight endurance times of between 24 and 48 hours, and maximum take-off weights of between 2,500 kg and 12,500 kg. These UAV systems can be referred to as High Altitude Long Endurance (HALE) UAVs. Several Medium Altitude Long Endurance (MALE) UAVs are also included in Item 1.A.2.

There are varying definitions of cruise missiles, which can fly at high altitude or close to the ground. Other UAV systems can and have been converted to carry warheads to attack targets, and as such are effectively cruise missiles for that specific mission. They also sometimes share similarities to cruise missiles such as rocket propulsion, appearance, and the ability to receive and transmit data and commands in flight. The critical difference between cruise missiles and other UAVs is that the latter are designed to be re-usable. As other UAVs are designed to return from missions, they tend to share many features with manned aircraft, such as mechanisms for safe landing and larger wings meant to maintain altitude and enhance endurance.



Figure 5: A High Altitude Long Endurance (HALE) Unmanned Aerial Vehicle (UAV). (U.S. Air Force)

The fundamental difference between cruise missiles and ballistic missiles lies in altitude of flight. Cruise missiles typically fly within the lower atmosphere (below 20 km), using aerodynamic lift to gain and maintain altitude. They tend to be less expensive and smaller than ballistic missiles and usually have guidance during the entire flight. The launch of a cruise missile is more difficult to detect than that of a ballistic missile. There are some ballistic missiles that share features with cruise missiles, such as additional guidance capabilities while in flight or lower trajectories, but these are typically well above the 20 km altitude maximum of cruise missiles.

It should be noted that while some systems may have listed payload and/or range thresholds that fall beneath the minimum 300 km and 500 kg requirements for this category, it is possible to sacrifice payload for increased range or range for increased payload, by increasing or decreasing the amount of fuel carried or via other modifications. This may lead to the item in question falling outside manufacturers' specifications or intended operational concept.

Method of Operation: UAV systems can be controlled in flight by an onboard navigation system, which can fly a pre-programmed route following waypoints. Alternatively, the course of the UAV system can be adjusted in-flight with commands from a ground-based system, relayed via the onboard data link. UAV ground stations include a flight control system (usually a joystick console), and a series of display monitors and recording equipment. Meanwhile, an onboard flight control system maintains the UAV system in controlled flight, adjusting the control surfaces to maintain the desired flight path.



Figure 6: A UAV armed with air-to-surface missiles. (General Atomics Aeronautical Systems, Inc.)

Cruise missiles use aerodynamic lift and fly within the lower atmosphere (below 20 km or 65,617 ft in altitude), and can change direction or altitude at any point in their flight trajectory. These characteristics – operating altitudes and maneuverability – are the crucial differentiators between cruise missiles and ballistic missiles. However as with ballistic missiles, cruise missiles have three flight phases – the boost phase, the cruise phase, and the terminal phase. Speed during the cruise phase can vary from Mach 0.5 (610 km/h at sea level) up to Mach 2.5 (3060 km/h at sea level or 2065 km/h at 15 km altitude).

A cruise missile can be launched from ground vehicles, usually referred to as a Transporter-Erector-Launcher (TEL), from ships, from submarines, or from aircraft. When launched from land and sea cruise missiles will use small rocket boosters to launch them from their canisters and accelerate them to flying speed.

Cruise missiles have the capacity to fly multiple trajectories, and often fly pre-planned missions specifically designed to defeat defenses by means of terrain masking or defense avoidance, and increasingly by use of stealth technology. Most cruise missiles contain a sensor system that guides them towards their targets by using terrain features or target signatures. Cruise missiles increasingly use inertial navigation systems, updated by satellite navigation receivers in addition to, or instead of, terrain-aided navigation systems to guide them to the vicinity of the target, where a terminal sensor is activated to home in on the target. Various types of sensors are used to detect distinctive target signatures or to match pre-programmed scenes of the target area. Once at the target, the cruise missile detonates the warhead or, if so equipped, dispenses sub- munitions.



Figure 7: An operational cruise missile on its checkout stand, showing its nose cone modified to lower radar returns and enhance aerodynamic performance. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

Other UAV systems can be based on an aircraft purpose-built for unmanned flight or can be a modification of a manned aircraft, either fixed-wing or helicopter. Depending on the UAV's means of takeoff, the aircraft can be hidden and launched from a variety of locations, including rugged airstrips, maritime vessels or standard airports.

Large UAVs are ~~re~~ usually equipped with several types of payloads, including sensor equipment, contain avionics and data links, and are supported by a ground component, consisting of mission control elements (MCEs) and launch and recovery elements (LREs), which includes a ground personnel crew of varied size depending on the complexity and number of systems requiring human operation. In operations, the collection of the UAV flight vehicle (with payloads and avionics) and its ground support component (including MCEs and LREs) is often referred to as an Unmanned Aerial System (UAS).

Typical Missile-Related Uses: While UAV systems were initially deployed most commonly for reconnaissance operations, technological advancements now enable UAVs to carry far greater payloads over large distances for long periods of time. Consequently, many UAVs are now designed specifically as multi-mission systems, capable of performing a variety of operational functions, including: intelligence, surveillance, and reconnaissance (ISR); target identification; scientific research, and combat operations / weapons delivery.

Cruise missiles typically are used specifically to deliver weapons payloads to a distance between 300 km and 5,500 km.

Other Uses: Some HALE UAVs are being used to support a mission to improve hurricane track and intensity forecasts. The HALE UAV can stay over severe weather patterns for long periods comparable to that of a satellite, but their proximity to the storm provides finer resolution data. In some instances MALE

UAVs are also being used to support Earth science missions and advanced aeronautical technology development.

Appearance (as manufactured): Many UAV systems, including target and reconnaissance drones, often look like airplanes without cockpits for pilots. Large UAV systems will vary in appearance because of their role-specific designs, but most will have common features, including large (and often slender) wing-spans of between 20 m and 40 m, and distinctive domes toward the front end of the fuselage housing avionics and electrical components, including satellite communication (SATCOM) antenna, line of sight transceiver antenna, navigation instruments and global positioning systems (GPS). Weaponized UAV systems will typically have external wing stations for payload carriage.

Complete UAV systems controlled under this item also may include manned aircraft that are modified to fly autonomously as optionally piloted vehicles. Such systems usually retain a cockpit, which is empty or filled with electronic equipment or payload during flight.

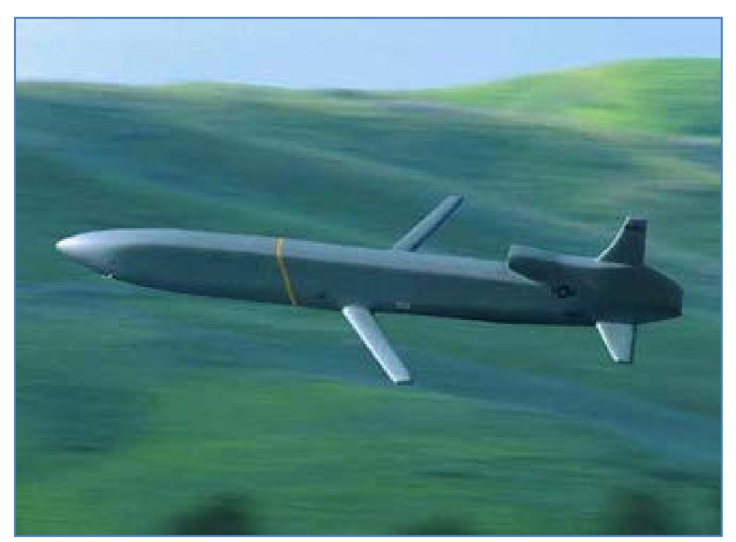


Figure 8: A computer-generated image of an air-launched cruise missile. (The Boeing Company)

Cruise missiles usually have a cylindrical or box-like cross-section and a fineness ratio (ratio of length to diameter) between 8 to 1 and 10 to 1. Most have lifting surfaces, or wings, and most use control fins at the tail (some have ailerons on the wings and/or canards), although the shape and size of these surfaces depends greatly on the intended flight regime and payload. Cruise missiles also tend to have a dull finish or coating to make them harder to detect, and advanced designs may incorporate special geometric surfaces to reduce radar reflections. Most of these features of a typical cruise missile are shown in Figure 8.

Appearance (as packaged): UAV systems, including cruise missiles, are manufactured in components or sections at different locations and by different manufactures, and assembled at a military site or a civilian production facility. These sections may vary in size from less than 10 kg and 0.03 m^3 to 150 kg and 0.1 m3 to 1 m^3 or larger, depending on the class of UAV.

Large UAV systems can be disassembled, packaged and shipped in heavy cardboard or customized containers; medium-size sections require heavy wooden crates. The wings of large UAVs are detached from the fuselage, and each section is crated separately for shipping by truck, rail, or cargo aircraft.

Most cruise missiles are shipped fully assembled in environmentally sealed metal canisters, which can also serve as launching tubes. Their wings are often folded either within or along the missile body, and the tail fins are often folded on longitudinal hinges in order to fit within the launch canister or on the launch platform and open after launch to control the missile.

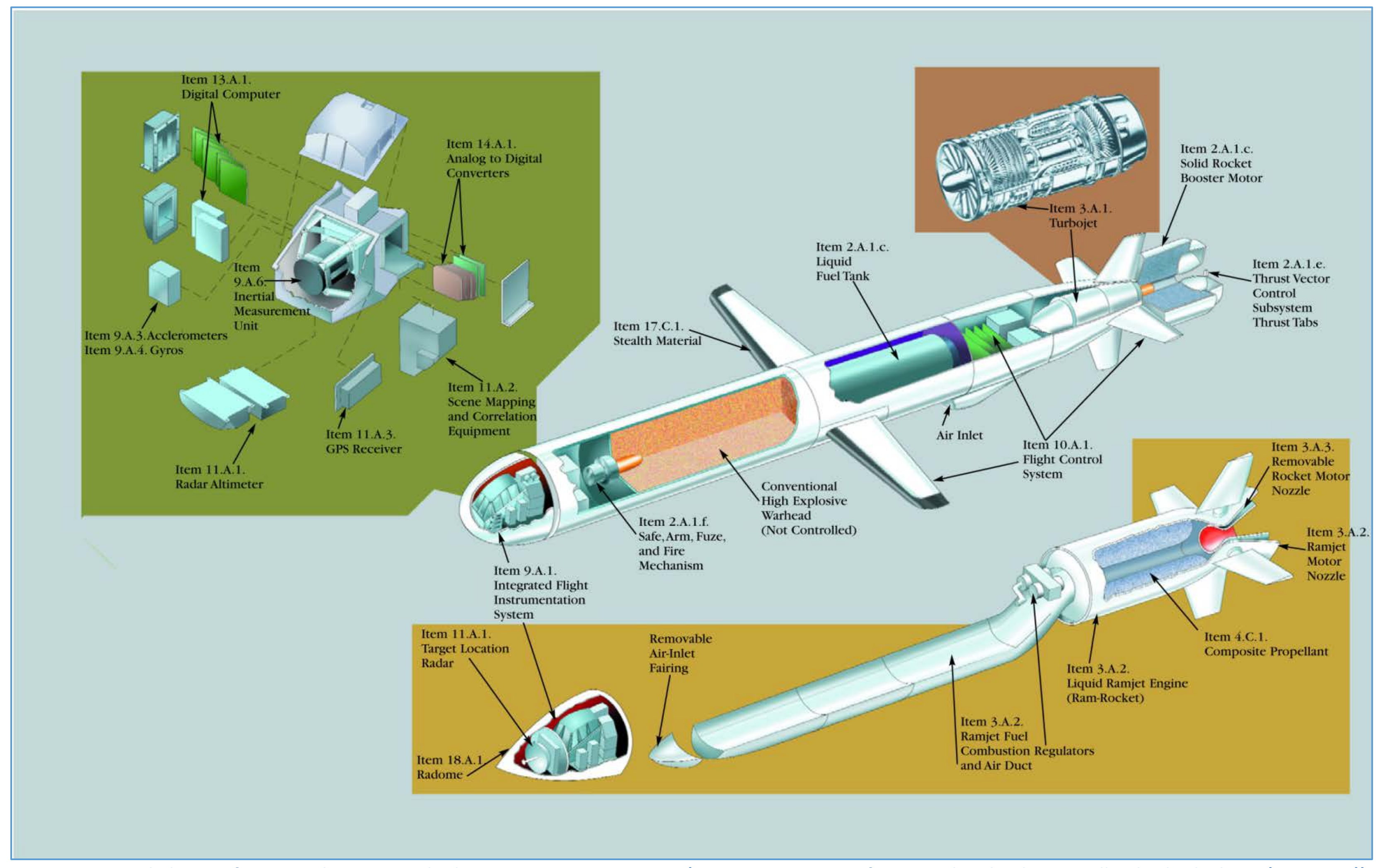


Figure 9: Expanded view of a notional cruise missile showing MTCR Annex items. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

1.B. Test and Production Equipment

1.B.1. "Production facilities" specially designed for the systems specified in 1.A.

- Argentina
- Brazil
- Canada
- China
- Egypt
- France
- Germany
- India
- Iran
- Israel
- Italy
- Japan
- North Korea
- Pakistan
- Russian Federation
- South Africa
- Republic of Korea
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global Production



Nature and Purpose: Specially designed production facilities include all the special equipment used for the production of complete rocket and UAV systems. There are many different kinds of specially designed production equipment for such delivery systems which, when integrated into installations for development or production, constitute production facilities. Some of the largest pieces of equipment in such production facilities are the jigs and fixtures used to ensure proper alignment of individual components during assembly. Molds, dies and mandrels are used extensively throughout the production process. These are designed for specific production processes and are usually unique to a part or component.

Method of Operation: Jigs and fixtures are used to receive, support, align, and assemble individual delivery system components. For rocket systems this includes fuel and oxidizer tanks, motor cases, and engine assemblies. For UAV systems this includes the airframe, wing spars, and engine assemblies. Overhead cranes are used to move the components from their shipping containers and dollies onto the assembly jig. Laser alignment instruments are sometimes built into fixtures in order to ensure precision fitting, and electrical and electronic test equipment for functional and operational testing are used as necessary during the assembly process.

Typical Missile-Related Uses: Production facilities are used to assemble a complete missile system from its subassemblies and component parts. At the end of each production step, mechanical and electrical fit and function tests are performed to verify that the assembly is ready for the next step. After a rocket is assembled and passes all production tests, it may be disassembled at prescribed body break points. These separated missile components are loaded into individual containers or crates for shipment to a facility for long-term storage or to the operational launch point for final reassembly and use. However, UAV systems, including cruise missiles, are typically shipped fully assembled to operational units (depending on the type of launch platform) or to storage depots for long-term storage.

Other Uses: Assembly jigs and fixtures are usually single-application items designed to produce one type of rocket or UAV system. It is usually not practical to modify them for other uses.

Appearance (as manufactured): Assembly jigs and fixtures used in the production of missile systems (such as that shown in Figure 10) are usually large and heavy structures. Their overall length and width are roughly 20% to 30% greater than the missile system that they are designed to assemble. Their weight may total hundreds or even thousands of kilograms.





Figure 10: ***Left:*** **A Space Launch Vehicle on an assembly jig. (Korea Times)** ***Right:*** **Modular jig supporting a cruise missile in final assembly.**

Appearance (as packaged): Assembly jigs and fixtures for large missiles are often too large and heavy to be packaged and shipped to the production plant as complete units. Instead, component parts are shipped separately in large crates or protected on pallets for assembly onsite. They will be securely fastened to the crate to restrain motion and prevent damage. Smaller jigs may be individually packaged on crates or pallets for shipment. Large factories may produce assembly jigs and fixtures on-site as part of their overall manufacturing effort.

Additional Information: Assembly jigs and fixtures built to receive and assemble missile components in a horizontal attitude require contoured surface pads or rollers to support the cylindrical body parts with minimal deformation. Assembly systems that are used to build a rocket in a vertical attitude require fewer body support fixtures but must have a high overhead clearance within the building to stack the components and move a fully assembled missile. The primary components of assembly jigs and fixtures are standard structural steel members. Their size and strength are dictated by the requirement to support and maintain alignment of the large and heavy missile components during assembly.

Jigs and fixtures are usually assembled by welding or bolting large steel plates and I-beams or tubular members together on the floor of the missile assembly building. In some cases, these fixtures are built on floating pads, not bolted to the floor; such pads isolate the structure from vibrations, which might otherwise cause misalignment of their precision reference points. Precision survey devices are used to ensure correct alignment.

Jigs and fixtures for UAV systems vary widely depending upon the complexity of the delivery system. Some UAVs use assembly methods similar to building a kit aircraft with structural foam and hand layup of either glass or carbon fabric. More sophisticated UAVs use production jigs and fixtures that resemble manned aircraft manufacturing with component cells feeding a pull-based assembly line.

1.C. Materials

None.

1.D. Software

1.D.1. "Software" specially designed or modified for the "use" of "production facilities" specified in 1.B.

•Argentina	•Brazil
•Canada	•China
•Egypt	•France
•Germany	•India
•Iran	•Israel
•Italy	•Japan
•North Korea	•Pakistan
•Russian Federation	•South Africa
•Republic of Korea	•Sweden
•Switzerland	•Ukraine
•United Kingdom	•United States

Global Production



Nature and Purpose: Production facility process software ranges from numerical control routines used for component manufacturing to Supervisory Control and Data Acquisition (SCADA) systems that monitor and control plant-wide functions and processes. Larger facilities may also employ a Manufacturing Execution System (MES) that manages all aspects of the manufacturing process from Production Definition to "As-Built" documentation. The MES sits on top of SCADA systems and the numerical control equipment to coordinate production processes.

Method of Operation: Numerical control routines reside on the controller of the automated equipment and typically perform a specific operation such as drilling holes in a motor case. SCADA systems integrate sensor information from a variety of analog and digital devices to coordinate process flow using dedicated computers and programmable logic controllers. Continuous flow propellant facilities require precise measurement of specialized ingredients, such as burn

rate modifiers, while the propellant is being mixed and transferred to the motor cases. The MES interfaces with the production facility to schedule production, track progress and report results to maintain operations.

Typical Missile-Related Uses: The production facility software is installed in computers that are connected to numeric control equipment, sensors and/or other automation used to produce missile components. None of this software is designed for use on the missile computer.

Other Uses: MES software that is used in missile production facilities may also be employed, with modifications, to control a non-missile related facility, manufacture automobiles or to manage other industrial processes where precise and repeatable tasks are required.

Appearance (as manufactured): Typically software used in production takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs and documents can contain this software and data.



Figure 11: Software in the form of a computer disc, a cassette tape, and written media. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs and documents containing missile production control software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software and documentation can be transmitted electronically over a computer network.

1.D.2. "Software" specially designed or modified to coordinate the function of more than one subsystem in systems specified in 1.A.

Note:

For a manned aircraft converted to operate as an unmanned aerial vehicle specified in 1.A.2., Item 1.D.2. includes "software", as follows:

a. "Software" specially designed or modified to integrate the conversion equipment with the aircraft system functions;

b. "Software" specially designed or modified to operate the aircraft as an unmanned aerial vehicle.

- Argentina
- Australia
- Brazil
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Pakistan
- Portugal
- Russian Federation
- Republic of Korea
- Switzerland
- Sweden
- United Kingdom
- United States
- Ukraine

Global Production



Nature and Purpose: The software used to coordinate the function of multiple subsystems on systems specified in 1.A. is typically flight control software. Flight software incorporated into the onboard computer collects velocity and position information provided by the navigation or guidance system and feedback from the control system, allowing the computer to calculate and issue steering corrections to the flight control systems. This software also determines when to perform other flight events, such as engine shutdown, staging and re-entry vehicle separation.

The software used in the conversion of a manned aircraft to operate as a UAV typically includes specially designed software to integrate the conversion equipment with the key aircraft systems and additional software to operate the converted UAV. The integration software allows the conversion equipment to communicate with the key aircraft systems in a similar manner to a pilot's input commands. The operation software may allow for control from the ground or autonomous flight of the aircraft.

Method of Operation: Flight software is installed in the missile system's computer and is tested prior to launch. During launch countdown, this software becomes active and takes control of the launch process, usually with first stage ignition. Once free of all launch platform signal connections, the missile is under the control of this software. All position or velocity signals generated by the navigation system, as well as

control system feedback, are sent to the flight computer which generates corrective signals to the flight control hardware. Engine pressures and general system health are monitored. For rocket systems, when the required velocity and position are sensed, the propulsion system is shut down. For ballistic missiles, when the arming signals are confirmed by the warhead, the re-entry vehicle may be separated from the airframe.

UAV system flight software controls the engine operation, issues steering commands to the flight control system, based on navigation information, and activates the payload (camera, weapon, etc.)

Typical Missile-Related Uses: Flight software is used in both complete rocket systems and UAVs (to include cruise missiles) to control the operation of all flight systems.

Other Uses: This software is uniquely prepared for individual types of rocket systems or UAVs and is not usually used in other types of applications.

Appearance (as manufactured): Typically software that controls more than one subsystem and that is specially designed or modified for use in systems specified in 1.A. takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing software that controls more than one subsystem and that is specially designed or modified for use in systems specified in 1.A. are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software and documentation can be transmitted electronically over a computer network or the internet.

1.E. Technology

1.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or "software" in 1.A., 1.B., or 1.D.

Nature and Purpose: "Technology" for the "development", "production" or "use" of equipment or "software" specified in 1.A., 1.B. or 1.D. includes "technical assistance" or "technical data." "Technical assistance" is the provision of instruction, skills, training, working knowledge or consulting services to a country developing rocket or UAV systems. "Technical data" include – but is not limited to – formulae, blueprints, technical reports or computer databases "not in the public domain". The purpose of "technology" is to provide end-users with the ability to indigenously develop the means for the "development", "production" or "use" of equipment or "software" specified in 1.A., 1.B. or 1.D.

Method of Operation: "Technology" and "technical assistance" are available in many forms. "Technical assistance" may consist of instruction provided by a person experienced in one or more subjects relating to controlled items (such as liquid propellant rocket engines) who acts as a trainer in a classroom on or near the production or test site or the use of a consulting service that specializes in aerospace material production directing the purchase of the right materials and equipment. A country may receive "technical assistance" by sending students to other countries to attend training and practice the skills necessary to build Category I systems. The manuals and materials received during training may qualify as "technical data".

Typical Missile-Related Uses: With limited exception, the "technology" required to build delivery systems is used only for those purposes. Sounding rockets used in weather research, with adjustments to payload and guidance, can be converted to ballistic missiles. The "technology" used in each device is very similar.

Other Uses: Some "technology" used to design, manufacture, and test UAVs may have functionality in the military or commercial aircraft industry.

Appearance (as manufactured): N/A

Appearance (as packaged): N/A

Category I - Item 2

Complete Subsystems Usable for Complete Delivery Systems

Category I – Item 2: Complete Subsystems usable for Complete Delivery Systems

2.A. Equipment, Assemblies and Components

2.A.1. Complete subsystems usable in the systems specified in 1.A., as follows:
a. Individual rocket stages usable in the systems specifed in 1.A.;

- Brazil
- China
- Egypt
- France
- Germany
- India
- Iran
- Iraq
- Israel
- Italy
- Japan
- Libya
- North Korea
- Pakistan
- Russian Federation
- Rep. of Korea
- Syria
- Ukraine
- United Kingdom
- United States

Global Production



Nature and Purpose: A rocket stage generally consists of either a solid rocket motor or liquid tanks with engines, along with various structural parts and control system components. Rocket motors or engines produce propulsive thrust to make the rocket launch and accelerate in flight. Solid propellants typically burn to exhaustion once ignited, while liquid engines can be shut down for more flexible trajectory control.

Large liquid rocket engines typically include high-performance pumps so that the combustion chamber and nozzle can be relatively compact by virtue of high pressure operation, while the large tanks remain lightweight due to thin walls consistent with low pressures. In contrast, the walls (case) of a solid rocket motor must be thicker to contain high combustion pressures. Solid propellant is typically denser than liquids, and the entire rocket motor is used to both store the propellant and act as the combustion chamber when ignited. These features permit a solid rocket stage to be compact, while avoiding unduly heavy structural mass.

Method of Operation: A launch signal either fires an igniter in the solid propellant inside the upper part of a solid rocket motor, or valves are opened to let liquid propellants into the combustion chamber of a rocket engine where they burn. Either way, high-pressure high-temperature gases escape at sonic speeds through a narrow throat at the rear of the rocket stage, then accelerate while expanding in a diverging nozzle. The momentum of the exhaust gases provides the thrust for the missile. Multi-stage rocket systems discard the lower stages as they burn up their propellant, in order to progressively lose unnecessary weight, thereby achieving greater range than comparably sized single-stage rocket systems.

Typical Missile-Related Uses: Rocket stages are essential components of most rocket systems, including ballistic missiles. Rocket stages are also used in missile and missile-component testing applications.

A key advantage of solid propelled stages is launch readiness, because the solid propellant is part of the rocket motor as manufactured. Liquid rocket stages typically require more time to prepare for launching, because propellants cannot in general be loaded in advance for long-term wet storage.

Rocket stages are used by space launch vehicles for earth departure, while smaller complete stages (upper stages) are used for maneuvering while in orbit or beyond low earth orbit.

Other Uses: N/A

Appearance (as manufactured): Solid propellant rocket stages (Figure 12) in the size range of interest for MTCR 2.A.1. are cylinders, usually ranging from 4 m to 10 m in length and 0.5 m to 4 m in diameter, and capped at each end with domes for structurally efficient containment of high pressures. Figure 1 shows a solid rocket stage being positioned onto a space launch vehicle. The forward dome usually has a threaded or capped opening for inserting an igniter. The center portion of the rear dome has an attached conical-shaped nozzle, or (rarely) there may be multiple nozzles. The cylinders (motor cases) generally are made of high-strength sheet steel, a composite of filament-wound fiber in a resin matrix, or a combination of both, and may include an internal insulating material such as cork or rubber sheet. Because solid rocket stages as manufactured contain high-density propellant, they are very heavy. The propellant grain may be visible through the nozzle, in the absence of any added coverings.

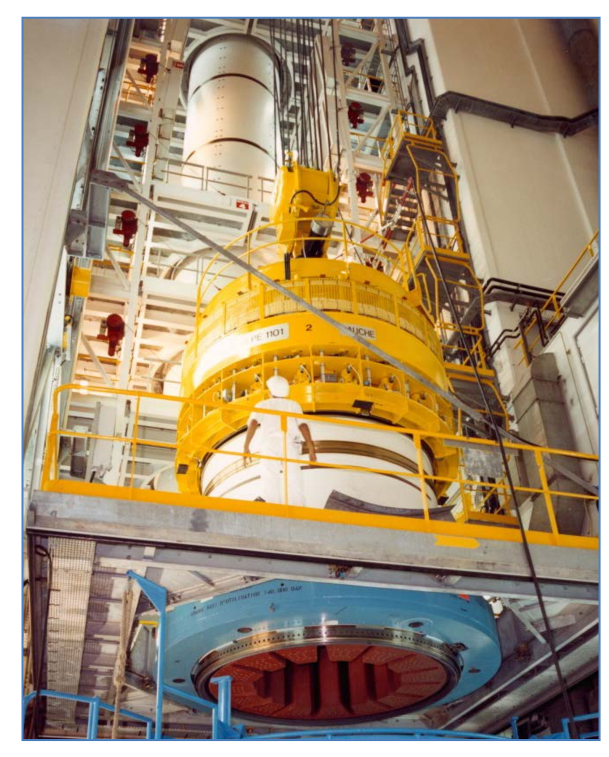


Figure 12: Solid propellant rocket motor stage being positioned onto a space launch vehicle (above). (European Space Agency)

Liquid propellant rocket stages typically consist of stacked cylindrical tanks, one for fuel and one for oxidizer, roughly illustrated in the cutaway sketch for Item 1.A.1., and shown externally in Figure 13. Rocket tank walls are thin metal, often with integral stiffeners on the inside (rings, etc.). The tank walls also serve as stage structure. Each tank has a dome at both ends, surrounded by additional structure extending beyond the tank ends for the purpose of joining tanks together within the stage (intertanks), and similarly for joining stages together (interstages). Sometimes a tank end is concave, fitting close to the convex dome of another tank.

One or more engines are at the rear of a liquid rocket stage, each one receiving both oxidizer and fuel through large pipes or ducts. A conical-shaped nozzle or nozzles are attached to the rear of each engine at the outlet of the combustion chamber. Propulsion parts include various valves and small tanks for

pressurized gases. Other rocket stage items are electrical systems and/or hydraulic systems for control and steering.

Appearance (as packaged): Virtually all rocket stages are shipped in containers or fixtures specifically designed for them. Smaller solid propellant rocket stages can be shipped in wooden crates with internal restraints and shock mounts. Larger solid propellant stages are more often shipped in specially designed metallic containers, usually cylindrical in appearance and sometimes filled with an inert atmosphere. Very large stages may be simply wrapped with a protective covering. Solid propellant stages are required to comply with international shipping requirements for explosives and have appropriate markings. Considering that solid rocket stages are nearly completely filled with high-density, rubber-like propellant, their mass typically exceeds one ton per cubic meter of stage volume.

Liquid rocket stages are shipped similarly, or in specially designed fixtures without external packaging. Because they are shipped without propellant or pyrotechnics, they may be transported as routine hardware without any constraints or warning labels, and they weigh significantly less than solid rocket stages. The shipping mass of an empty liquid rocket stage might be less than 100 kg per cubic meter of total stage volume.

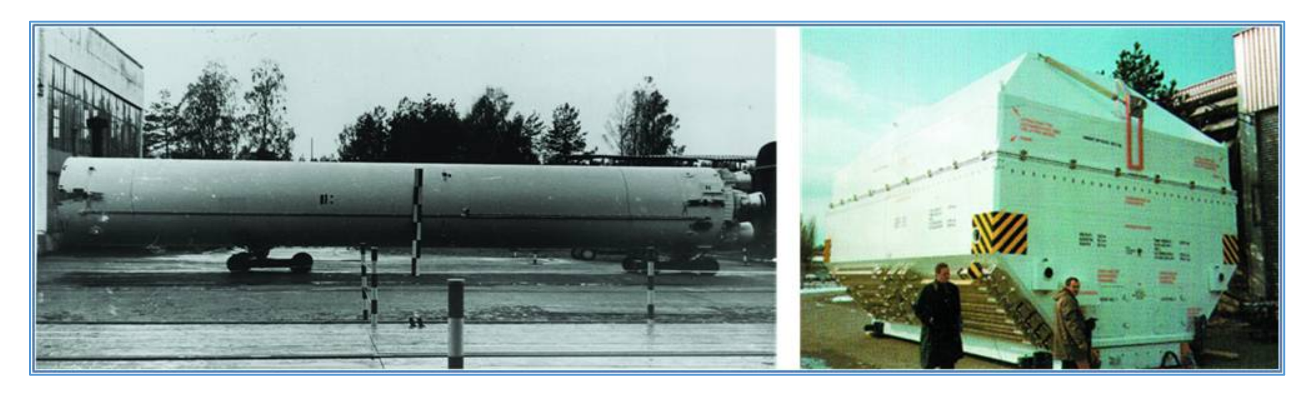


Figure 13 *Left:* The first stage of a liquid-fueled ICBM. *Right:* A shipping container for a liquid-fueled upper stage. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

2.A.1.b. Re-entry vehicles usable in the systems specified in 1.A., and, as follows, equipment designed or modified therefor, except as provided in the Note below 2.A.1. for those designed for non-weapon payloads:

1. Heat shields, and components therefor, fabricated of ceramic or ablative materials;
2. Heat sinks and components therefor, fabricated of light-weight, high heat capacity materials;
3. Electronic equipment specially designed for re-entry vehicles;

- China
- France
- Germany
- India
- Israel
- Russian Federation
- United Kingdom
- United States

Global Production



Nature and Purpose: While many short-range missiles approach their targets as one complete piece, longer range missiles drop rocket stages along the way, leaving their warheads to separately re-enter the atmosphere. Re-entry vehicles (RVs) are sharp- to blunt-tipped, conical-shaped bodies (Figure 14) that house and protect the missile payload, or warhead, from the high heat and vibration experienced during re-entry. RVs also carry the arming, fuzing, and firing equipment that will detonate the warhead when it reaches the target. The RVs are released from the payload section of the missile and travel on a ballistic trajectory, entering the atmosphere at speeds between Mach 2 and 20, depending on range. Some RVs, known as Maneuvering Re-entry Vehicles (or MARVs) also carry guidance and control equipment that allows them to maneuver to either home in on targets or avoid defenses.

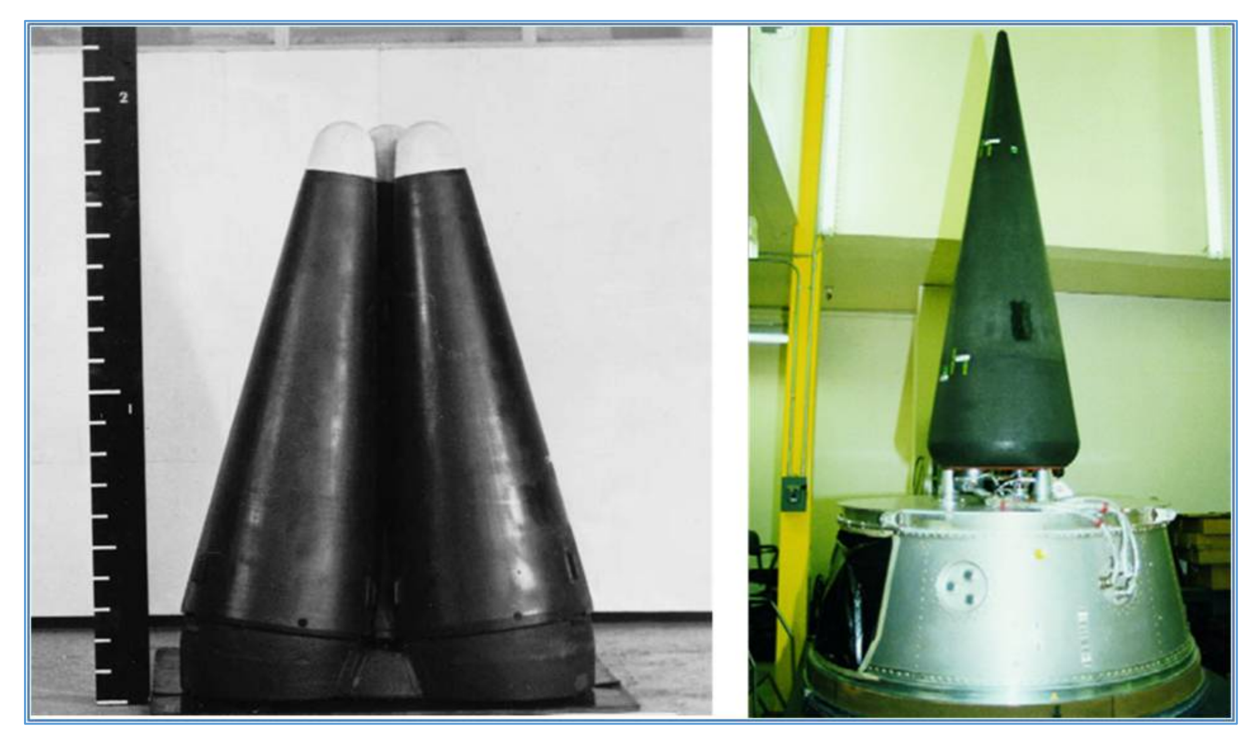


Figure 14: Left: Three modern RVs attached to their mounting flange. Small fins at the aft end spin-stabilize the RVs as they re-enter the atmosphere. Right: A modern RV on its payload support bulkhead. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

Method of Operation: A missile may carry one or more RVs in its forward, or payload, section. A single RV might itself be the tip of a missile. Two or more RVs, are usually covered with a larger conic or ogival shroud or nose fairing that covers the entire payload section at the top of the missile during launch and ascent through the atmosphere. After ascent drag and heating subside, the shroud or fairing is jettisoned. A post-boost system carrying the RVs may sequentially orient each RV and release it. Reoriented RVs are usually spun up about their longitudinal axis so they re-enter the atmosphere in a gyroscopically stable, nose tip-forward attitude and thereby have greater target accuracy. Non-oriented RVs tumble on their trajectories during re-entry until aerodynamic forces stabilize them with their nose tips forward. The conic surface of the nose tip and RV are usually covered with heat shield material to withstand the high heat of re-entry.

A MARV using terminal guidance may implement a maneuver as it re-enters the atmosphere to decrease its speed, and then orient itself to bring a sensor to bear on the target. MARVs may use control surfaces, change their aerodynamic shape, change their weight distribution, or use reaction jets to improve accuracy or to follow a path unpredictable to a missile defense system. Hypersonic glide vehicles are one potential type of MARV that has received increased worldwide attention for research of aerodynamic maneuvering.

Typical Missile-Related Uses: The principal function of an RV is to achieve accuracy and provide thermal and structural protection to the warhead and the arming, fuzing, and firing system during re-entry.

Other Uses: RV structures intended for weapons have no non-military applications. Some RV components

have commercial applications, most notably heat-shield materials used in furnaces, steelmaking, and engines. Certain RV-like configurations have been used for the return of manned space vehicles. The materials and technologies are overlapping, but these have not been designed for the re-entry conditions required of a weapon system. In contrast to missile RVs, returning crews and cargo from orbit imposes strict limits on peak deceleration and on terminal speeds. The necessary heat shielding is often referred to as thermal protection systems (TPS).

Appearance (as manufactured): RVs are conical-shaped structures (some with several cone angles), usually with a hemispherically rounded nose tip. The base, or rear, of the vehicle may be hemispherical or less rounded. Small fins for aerodynamic stability may be attached at several locations at the rear of the conical surface. The conic surface is covered with a heat shield, which may be naturally colored (black for carbon-based heat shields, tan or yellow for silica-based shields) or may be painted. Advanced technology RVs are usually long, thin cones with sharp nose tips (see Figure 15). They may have small ceramic inserts that serve as antenna windows at several locations on the conical surface. These are normally positioned near the rear of the RV to avoid the heat and shock of re-entry.

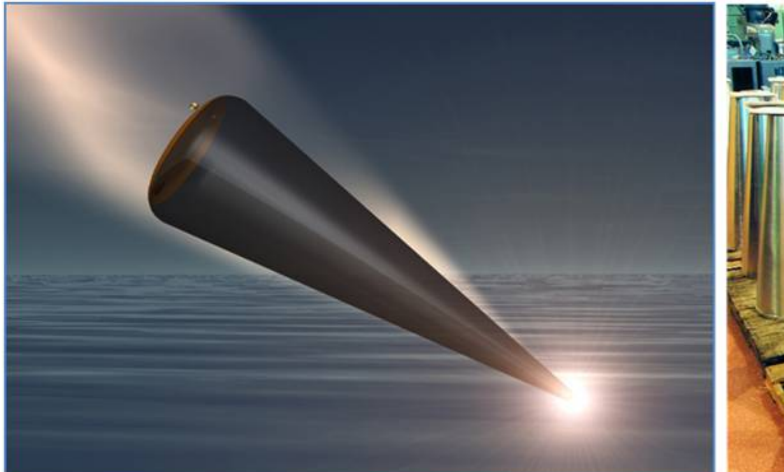




Figure 15: ***Left:*** **A graphic depiction of an Intercontinental Ballistic Missile (ICBM) re-entry vehicle. (U.S. Air Force)** ***Right:*** **Modern RV midsections during manufacture. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))**

RVs intended for multiple-warhead missiles are usually less than 3 m long and less than 1 m in base diameter. RVs used on missiles carrying a single warhead often have diameters equal to that of the uppermost stage, and typically have lengths between 1 m and 4 m. RVs, including the warheads they contain, typically range in mass from slightly less than 100 kg to roughly 1,000 kg.

The RV structure is usually manufactured in several sections for ease of warhead installation and field maintenance. The forward-most section typically contains some or all of the fuzing electronics, the middle section carries the warhead, and the aft section commonly contains timers, additional arming system electronics, and the spin system for those RVs that are spun up after their release from the booster, platform or bus.

Appearance (as packaged): The RV sections are usually transported together in special containers, either wood or steel, not much larger than the RV itself. They are shock-isolated and supported at several

locations inside the shipping container, which may be environmentally controlled. In the field, RVs receive special handling because they contain warheads. They are almost always transported separately from the booster and mated to the booster only at the launch site. If there isn't a fixed launch location, missiles already have their RVs installed, e.g. if they are intended to be road mobile or carried on submarines.

- China
- France
- India
- Israel
- Russian Federation
- United Kingdom
- United States

Global Production



Heat Shields and Heat Sinks

Nature and Purpose: As atmospheric drag slows a high-speed object, the kinetic energy is converted into heat. Heat shields and heat sinks are form-fitting, protective overlays on RVs. Their primary purpose is to protect the RV payload from destruction by the high temperatures caused by air compression and friction as the RV re-enters the atmosphere.

Method of Operation: Heat shields protect the RV and its payload by ablation or insulation. In the case of ablation, the heat shield absorbs the heat and its surface decomposes or vaporizes, transferring heat into the passing airflow. This process keeps the underlying layers cool until they in turn are exposed to the high temperatures. Heat sinks use their mass to simply absorb the heat of re-entry and thereby decrease heat transfer to the payload.

Typical Missile-Related Uses: Heat shields or heat sinks provide an external protective coating for RVs and may serve as the aeroshell. Their composition and thickness are a function of the re-entry velocity, itself a function of the operational range of the rocket system. For ranges less than approximately 1,000 km, simple steel skins can serve as heat sinks. For ranges greater than 1,000 km, composite heat shields or much larger heat sinks are required.

Other Uses: Heat shields and components are used in furnaces and engines. The equipment used to make them can be used to make composite tubing for oil drilling. Heat sinks and related technology have many commercial applications, including power production and electronics. However, there are no commercial uses for heat shields or heat sinks designed to fit missile RVs. Carbon-based material suitable for heat shields is also used to line engine nozzles and in the manufacture of disc brakes.

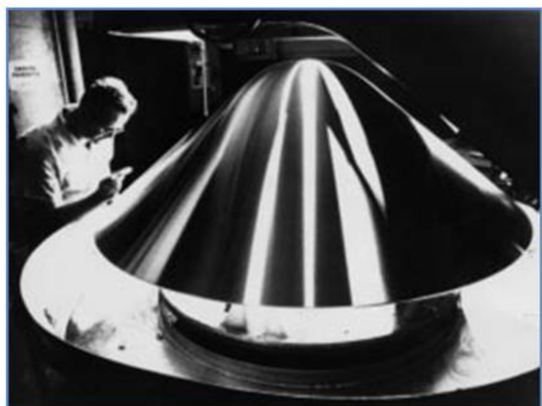



Figure 16: Left: A beryllium-copper heat sink. (National Atomic Museum) Right: A prototype heat shield for use on vehicles during re-entry from lunar and low-Earth orbit missions. (Boeing)

Appearance (as manufactured): Heat shields and heat sinks usually have the same size and shape as their underlying RVs. In some cases, they cover only the forward portion of the RV nose cone. Sizes for missile applications range from 1 m to 3 m in length and less than 1 m in diameter. Shields are generally conical or ogival, with pointed or rounded noses. They are either bonded to the RV or slipped over it in order to achieve a close fit. Their surfaces sometimes display body joints and may have antenna windows installed in them at one or more locations. These windows permit radar or other radio-wave transmissions to occur during re-entry. Figure 16 illustrates the contrast between RV heat sinks or shields, and their counterparts for conical space vehicles. Heat shields cover the conical end of a missile RV, while commercial or manned space missions require the heat shield to be on the blunt end of the reentering space capsule to ensure a safe return from space.

Appearance (as packaged): Missile RV heat shields, heat sinks, and their components are small enough to be packaged in conventional shipping boxes or crates for protection from damage. If the heat shields or heat sinks are bonded to the RV, the packaging must support the full weight of the RV in order to protect the entire payload from shock and vibration as well as to protect the surface of the heat shield from damage in shipping.

- China
- France
- India
- Israel
- Russian Federation
- United Kingdom
- United States

Global Production



Electronic Equipment Specially Designed for Re-entry Vehicles

Nature and Purpose: RVs contain various kinds of electronics. They must have a subsystem to safe, arm, fuze, and fire the warhead (the SAFF subsystem). They may also have radars, telemetry equipment, sensors, guidance systems, computers, and defensive systems such as radar jammers and chaff dispensers. RV electronics are characterized by their relatively small size and their ability to withstand the high temperature, high acceleration, and strong vibration encountered during both missile launch and especially during atmospheric re-

entry. In addition, RVs for nuclear warheads use electromagnetic pulse (EMP) protected circuits and radiation hardened microcircuits as described in Items 11.E.1. and 18.A.1., respectively.



Figure 17: Left: An RV radar antenna set packaged for shipment. Right: A portion of RV radar electronics. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

Method of Operation: The many different types of RV electronic equipment operate much the same as any corresponding avionics equipment; however, a battery supplies power for the RV electronic equipment. A power supply converts the battery voltage to whatever is required by the various electronics within the RV. Additionally, all the electronic equipment onboard the RV must be designed to operate reliably in harsh environments.

Typical Missile-Related Uses: Virtually all the electronic components in RVs are specifically designed for them. The most important RV electronic components are those of the SAFF system; their functions are described in 2.A.1.f. below. Other electronic equipment is optional and depends on mission requirements. Cables and connections are ordinary but necessary accessories. RVs designed to operate in the hostile X-ray and neutron environments created by nuclear defenses must use highly protected electronic components and cabling, which is clearly identified in its product specifications as capable of operation in such hostile environments.

Other Uses: Barometric switches, power conditioners, and relays not specially designed for RVs are used in general aviation. Standard cabling and connectors (not nuclear hardened) are common to thousands of commercial end uses. In general, distinguishing commercial electronic equipment from equipment specially designed for RVs is difficult because the biggest differences – nuclear hardening, temperature operating limits, and vibration requirements – are not usually visible.

Appearance (as manufactured): The usual components of an RV electronics package are unremarkable in appearance. The largest and most distinctive part is probably the battery, which may be roughly half the size of an automobile battery but is often considerably smaller. Most of the remaining electronic components are small and are usually housed in aluminum boxes. The SAFF subsystem is assembled by the RV manufacturer and is unlikely to be obtained as a prepackaged unit. Very advanced RV designs can

use active/passive seekers (radar and optical sensors) coupled to active control systems and stored maps of target features. Such equipment may have a disk, conical, or truncated-cone appearance because it is designed to fit tightly into an RV. Any indication of special capabilities to withstand high acceleration or severe vibration, such as shock isolation pads, may suggest a missile application.
Appearance (as packaged): Military-grade electronic parts are packaged in sealed bags or containers used to protect the electronics from moisture, shock, and static electricity. Foam-lined boxes, crates, or metal suitcases may also be used for packaging.

2.A.1.c. Rocket propulsion subsystems, usable in the systems specified in 1.A., as follows;

1. Solid propellant rocket motors or hybrid rocket motors having a total impulse capacity equal to or greater than 1.1 x 10^6 Ns;

2. Liquid propellant rocket engines or gel propellant rocket motors integrated, or designed or modified to be integrated, into a liquid propellant or gel propellant propulsion system which has a total impulse capacity equal to or greater than 1.1 x 10^6 Ns;

Note:

Liquid propellant apogee engines and station-keeping engines specified in 2.A.1.c.2., designed or modified for use on satellites, may be treated as Category II, if the subsystem is exported subject to end-use statements and quantity limits appropriate for the excepted end-use stated above, when having a vacuum thrust not greater than 1kN.

- Brazil
- China
- Egypt
- France
- Germany
- India
- Iran
- Israel
- Italy
- Japan
- Norway
- Pakistan
- Russian Federation
- Rep. of Korea
- Sweden
- Ukraine
- United Kingdom
- United States

Global Production



Solid Propellant Rocket Motors

Nature and Purpose: Solid propellant rocket motors contain both the fuel and the oxidizer inside a single motor casing, or case. No tanks, pipes, pumps, or valves are needed because the fuel and oxidizer are pre-mixed in the proper ratio and cast to make a propellant grain, a solid form with a hollow core, which is ignited internally. The outer casing of the rocket motor often serves as the form in which the propellant is cast. The case acts as a pressure vessel during operation, and is the main structural member that transmits the thrust to the payload. Solid rocket motors are cost effective and low maintenance; they can be easily stored for many years, and are capable of rapid deployment and launch.

Method of Operation: Once ignited, the propellant burns over its exposed surface area inside a hollow chamber running down the center of the motor. The hot expanding gases rush out the nozzle end at very high speed and provide thrust. Usually the propellant burns until it is depleted. Some motors have the

option to terminate thrust early by opening holes in the motor casing and venting the gases out the sides or through the top.

Typical Missile-Related Uses: Rocket motors provide the thrust to accelerate missiles to the velocity required to reach the intended target or to operate the next missile stage. The requisite product of thrust and time (impulse, which is momentum) can be achieved by one large rocket motor or by clusters of smaller motors, although a cluster would be less effective for the same total mass.

Some space launch vehicles have used solid propellant rocket motors for additional thrust in the early phases of launch. Orbit raising from geosynchronous transfer orbit (GTO) to geostationary earth orbit (GEO) has sometimes been accomplished with solid rocket motors referred to as “apogee kick motors”.

Other Uses: Space applications of solid propellant rocket motors have included unmanned lunar landing (Surveyor circa 1965), and orbit insertion at Venus (Magellan 1989). In test facilities, solid rocket motors have been used to achieve high accelerations and high speeds, in particular to push rocket sleds that accelerate a test object on a track along the ground.

Appearance (as manufactured): Solid rocket motors of greatest concern for missile proliferation appear as cylindrical tubes, often with domes at both ends for structural efficiency in withstanding operating pressures. One dome could have a small hole for attaching the igniter; the other dome could have a larger hole for attaching the nozzle. The igniter may or may not be installed before shipment; if not, the hole is covered by a plate made of steel or other material. The nozzle is usually attached before shipment and sealed with an environmental plug to protect the propellant from humidity and other environmental effects. This plug also prevents visual or any unauthorized physical access to the propellant in the motor case.

When installed, both the igniter and the nozzle are usually bolted in place. A modern solid rocket motor used in space launch vehicles and complete with a nozzle is shown in the top left of Figure 18. Approximately 400 kg of propellant is required to achieve the 2.A.1.c. threshold impulse of 1.1 x 10^6 N-s, assuming an exhaust velocity of 2750 m/s. Rocket motors containing this quantity of propellant would be approximately 2 m in length if the diameter is 0.5 m (roughly one ton per cubic meter of stage volume). A rocket motor of this size would usually have a steel case, although composite cases made of glass, carbon, or para-aramid fiber are possible.

Appearance (as packaged): Solid rocket motors are usually shipped in steel or aluminum containers or wooden crates. Crates have cradles at several points to support the weight of the motor and are usually lined with foam or cushioning material to protect the motor during shipment. Rocket motors are sometimes packaged in an inert atmosphere to keep the propellant protected from moisture. These containers are typically hermetically sealed, pressurized, and made of aluminum. Temperature storage limits are stated on labels to ensure longevity of the motors. Solid rocket motors have a thick, usually braided, metal strap with clamps at either end leading from somewhere on the motor case to the local static ground. This strap discharges any static electricity buildup and helps avoid fires and explosions. When shipped, the motor is grounded to the shipping container, and the container is grounded to the local ground.







Figure 18: ***Top left:*** **A re-usable solid rocket motor for space vehicle use. (ATK)** ***Bottom left:*** **Solid propellant rocket motors with total impulse close to the lower limit of Item 2 control. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))** ***Right:*** **A pressure-fed liquid rocket engine. (Aerojet)**

Liquid Propellant Rocket Engines

- China
- France
- India
- Iraq
- Japan
- Libya
- North Korea
- Russian Federation
- Ukraine
- United Kingdom
- United States

Global Production



Nature and Purpose: Liquid propellant rocket engines burn fuel and oxidizer, which is fed to them from separate tanks in the proper ratio through pipes, valves, and sometimes pumps. Thus, these engines are much more complex than solid propellant motors and can contain many precision-machined and moving parts.

Unlike solid rocket motors, liquid rocket engines typically can be shut off and restarted. Some liquid rocket engines can be re-used after refurbishment, while few solid rocket motors are designed to be re-usable. Liquid rocket engines are typically preferred for large space launch vehicles because they deliver more impulse for a given total propellant mass (more thrust for a given mass flow). However, they are more difficult to manufacture, require more maintenance, and take longer to prepare for launch than solid rocket motors. Fuel and oxidizer can also be difficult to handle and store because they are often toxic, corrosive, or cryogenic.

Method of Operation: Before launch, fuel and oxidizer tanks need to be filled with liquid propellants and pressurized with a gas in their ullage. Cryogenic propellants must be flowed through engine parts to chill them to liquid temperatures prior to ignition. If a pump is used, it is started along with the opening of valves to let propellants flow. Fuel and oxidizer are forced into the injector head, then through small holes for mixing in the combustion chamber. One typical method of mixing is for many small streams of liquid fuel and oxidizer to point toward each other in pairs just inside the combustion chamber near the injector face. Upon ignition, the mixture fully vaporizes and burns, then the hot, expanding gases rush out through the nozzle at very high velocity to deliver thrust to the missile. The thrust loads are transmitted from the combustion chamber through various structural elements attaching the engine to the rocket stage.

Typical Missile-Related Uses: Rocket engines provide thrust to accelerate missiles to the velocity required to reach the intended target. On a given stage of a missile, the requisite thrust can be achieved by one large rocket engine or by multiple smaller engines. Smaller liquid rocket engines might be used for maneuvering re-entry vehicles.

Liquid rocket engines are commonly used on space launch vehicles, where the large ones (e.g. a million newtons thrust) usually have pumps to feed high-pressure combustion chambers from low-pressure tanks. Upper stages use liquid engines that are successively smaller. Third stages are more likely to use higher tank pressures and lower combustion pressures, in order to avoid the complexity of pumps.

Other Uses: Smaller liquid rocket engines are widely used for orbit maneuvering and orbit maintenance for satellites and other spacecraft, typically without pumps.

Appearance (as manufactured): Liquid rocket engines are characterized by a cylindrical or spherical

combustion chamber to which a converging/diverging nozzle is attached. The nozzle is usually larger than the rest of the engine (Figures 18 and 20). Nozzles cooled by propellants flowing within may have sheet metal walls held apart by a corrugated sheet metal, or be composed of a bundle of contoured metal tubes. Uncooled nozzles are made of a refractory metal or an ablative composite material. The injector, a flat or curved plate with a large number of individual holes, can often be seen by looking into the nozzle to the top of the combustion chamber. An example injector is shown in Figure 20. A number of pipes, tubes, and pumps are attached to the top and sides of the combustion chamber. While Figure 20 shows a second stage engine having pumps powered by hot gas turbines, the liquid engine in Figure 18 is smaller and does not use pumps.

Appearance (as packaged): Liquid rocket engines are rugged devices, but they must be protected from shock and moisture. Typical containers include large wooden crates and metal containers.

Hybrid Rocket Motors

Nature and Purpose: Hybrid rocket motors (Figure 19) use both solid and liquid propellants, usually a solid fuel and a liquid oxidizer. Because flow of the liquid oxidizer can be controlled, hybrid motors can be throttled or shut down completely and then restarted. Hybrid rocket motors thereby combine some of the simplicity of solid rocket motors with the controllability of liquid rocket engines.



Figure 19: A hybrid sounding rocket motor. (NASA)

Method of Operation: Hybrid rocket motors use either pressurized tanks or pumps to feed oxidizer into the combustion chamber, which is lined with solid fuel. The pumps are driven by a gas generator powered by its own fuel grain or some other source of fuel. The liquid oxidizer burns the solid fuel inside the hollow chamber, and the hot, expanding gases are expelled through the nozzle at supersonic speed to provide thrust. As in a solid propellant rocket motor, the outer casing of the combustion chamber is protected from much of the heat of combustion by the fuel itself because it burns from the inside outward. Nozzles and motor cases for hybrids are similar to their corresponding items for solid rocket motors, e.g. the case must withstand combustion pressure.

Typical Missile-Related Uses: Hybrid rocket motors may be used to power space launch vehicles, sounding rockets and ballistic missiles.

Other Uses: N/A

Appearance (as manufactured): A hybrid rocket motor has an oxidizer injector mounted in the top of the high-pressure motor case and a converging/diverging nozzle at the bottom. The injector has valves and piping either from a pressure tank or from a tank and an associated pump. The combustion chamber is usually fabricated either from steel or titanium, which may be black or gray, or from filament-wound

graphite or glass epoxy, which is usually yellow or brown. The chamber is lined with thick, solid propellant having one of a variety of configurations and looking like a single cylinder with a hollow center, concentric cylinders, or wagon wheels. Nozzles are made of ablative material, which is often brownish, or high-temperature metals, and they may have high-temperature inserts in their throats (see Figure 9).

Appearance (as packaged): Hybrid rocket motors may be shipped fully assembled or partially assembled, with tanks and associated hardware packaged separately from the combustion chamber and attached nozzles. Fully assembled units are packaged in wooden crates; components are packaged in wooden crates or heavy cartons. Legally marked crates are labeled with explosives or fire hazard warnings because the missiles are fueled with solid propellant. However, because motors contain only fuel and no oxidizer, they are less hazardous than normal solid propellant rocket motors.

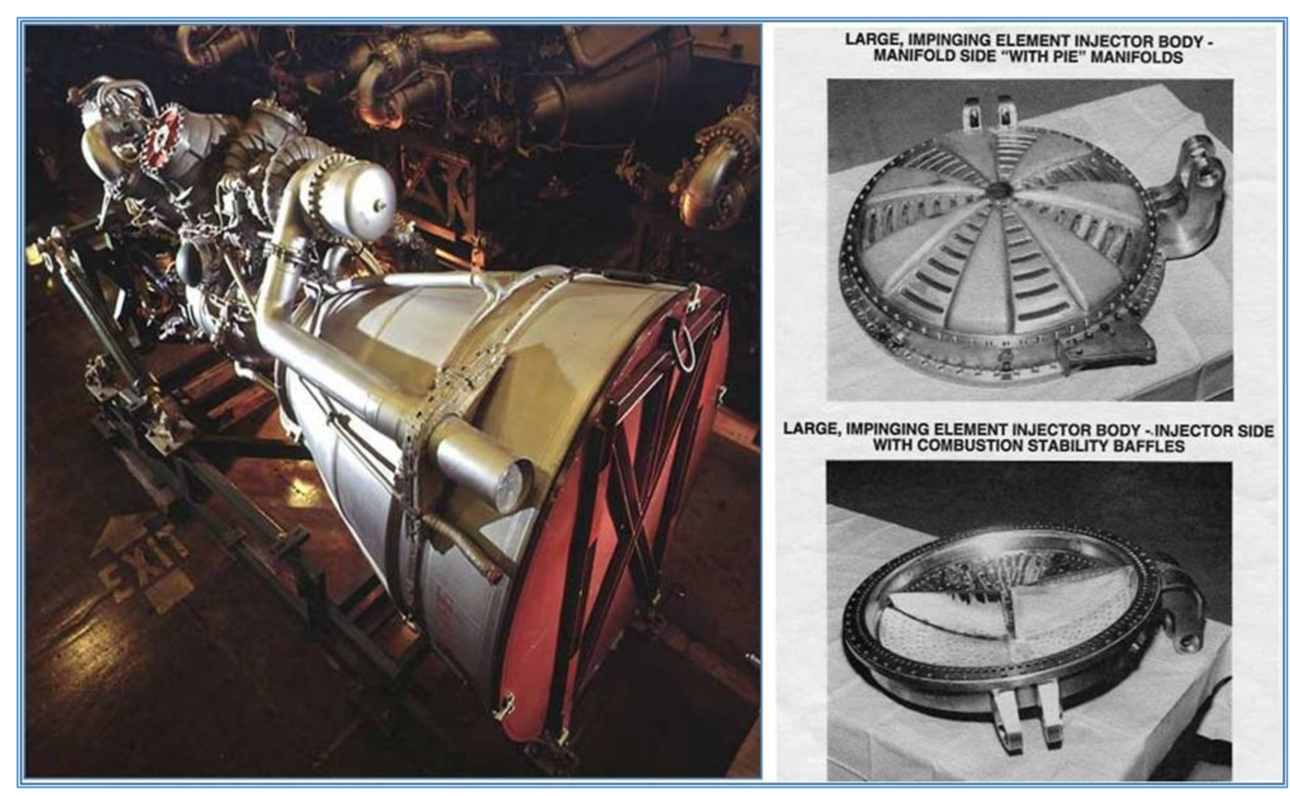


Figure 20: *Left*: A second-stage oxygen/kerosene liquid propellant rocket engine. (Aerojet) *Right*: The dome of an injector head (top picture) and its underside, showing the injectors and baffles (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

Gel Propellant Rocket Motors

Nature and Purpose: Gel propellants, along with their motors, thrusters, and propulsion subsystems, are a special case of their liquid propellant counterparts. If fuel and oxidizer tanks happen to break open, liquid propellants can easily flow together and mix, resulting in a large fire. Gel propellants do not flow and mix so easily, so gel propulsion offers safety in storage for applications that need features of liquids (versus solids), such as the capability for a variety of motors or thrusters to be rapidly turned on and off using valves. Another potential feature of gel propellants is that the propellants can contain additives for

improved energy. While solid particles of energetic materials would settle out in a liquid, such particles tend to remain suspended and hence evenly mixed in a gel propellant.

Method of Operation: Motors for gel propellants, and their parts such as injectors and thrust chambers, are similar to their liquid counterparts. Design details differ because higher pressures are needed to make gel propellants flow through narrow passageways, or conversely passageways need to be larger. While there might be exceptions, gel propellants are more likely to be used with pressure-fed propulsion, given that gels would not easily flow from low-pressure tanks in order to feed pumps. Similarly, gels do not naturally drain from a tank like liquids. Therefore, tanks for gel propellants are likely to have moveable separators such as diaphragms or pistons between the propellant and the pressurant gas.

Typical Missile Related Uses: The most likely use for gel propellants is for small propulsion subsystems, such as small missiles, upper stages of ballistic missiles, and maneuvering re-entry vehicles. Given the need for high pressures relative to flow, gel propellants are more likely to be used with relatively high tank pressures and other features that add weight to tanks. For these reasons, gels are more appropriate for small propulsion subsystems than for large rocket stages.

Other Uses: N/A.

Appearance (as manufactured): Motors and propulsion subsystems for gel propellants are very similar to their counterparts as built for liquid propellants. The size is relatively small as noted above.

Appearance (as packaged): Packaging needs to be specialized to protect against damage, especially for missile subsystems that are loaded with propellants. While complete liquid propulsion subsystems would not be shipped while loaded, the relative safety of gels potentially permits shipping when loaded.

2.A.1.d. 'Guidance sets', usable in the systems specified in 1.A., capable of achieving system accuracy of 3.33% or less of the "range" (e.g. a 'CEP' of 10 km or less at a "range" of 300 km), except as provided in the Note below 2.A.1. for those designed for missiles with a "range" under 300 km or manned aircraft;

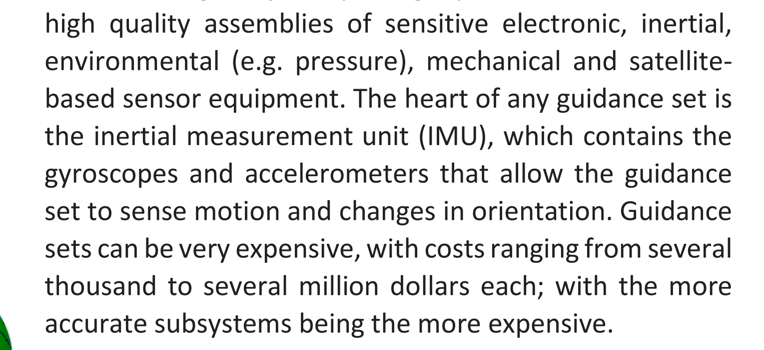
Technical Notes:

1. A ´guidance set´ integrates the process of measuring and computing a vehicle's position and velocity (i.e. navigation) with that of computing and sending commands to the vehicle's flight control systems to correct the trajectory.

2. ´CEP´ (circle of equal probability) is a measure of accuracy, defined as the radius of the circle centred at the target, at a specific range, in which 50 % of the payloads impact.

- Canada
- France
- Israel
- North Korea
- Ukraine
- United States
- China
- India
- Japan
- Russian Federation
- United Kingdom

Global Production



Nature and Purpose: A guidance set automatically steers vehicles along a trajectory or flight path. Guidance sets are high quality assemblies of sensitive electronic, inertial, environmental (e.g. pressure), mechanical and satellite-based sensor equipment. The heart of any guidance set is the inertial measurement unit (IMU), which contains the gyroscopes and accelerometers that allow the guidance set to sense motion and changes in orientation. Guidance sets can be very expensive, with costs ranging from several thousand to several million dollars each; with the more accurate subsystems being the more expensive.

Method of Operation: Guidance sets are calibrated and provided with information on the vehicle's position, velocity, and orientation prior to launch. After launch, inertial instruments sense accelerations and rotations of the vehicle, and usually convert these into electrical signals. A computational device converts these signals into deviations from the programmed flight path and issues commands to the flight control system to correct the course. However, because of errors in the inertial instruments themselves, the missile tends to veer off course over time. Guidance sets that drift off course less than 3.33% of range traveled are controlled under this item. Other guidance aids such as a Global Navigation Satellite System (GNSS) receiver, terrain reference systems, or gyro-astro compasses can be used to provide one or more mid-course updates on location or orientation to the guidance computer, thereby increasing accuracy. (Navigational equipment, including update equipment, is covered in Item 9.A. of the MTCR Annex.)

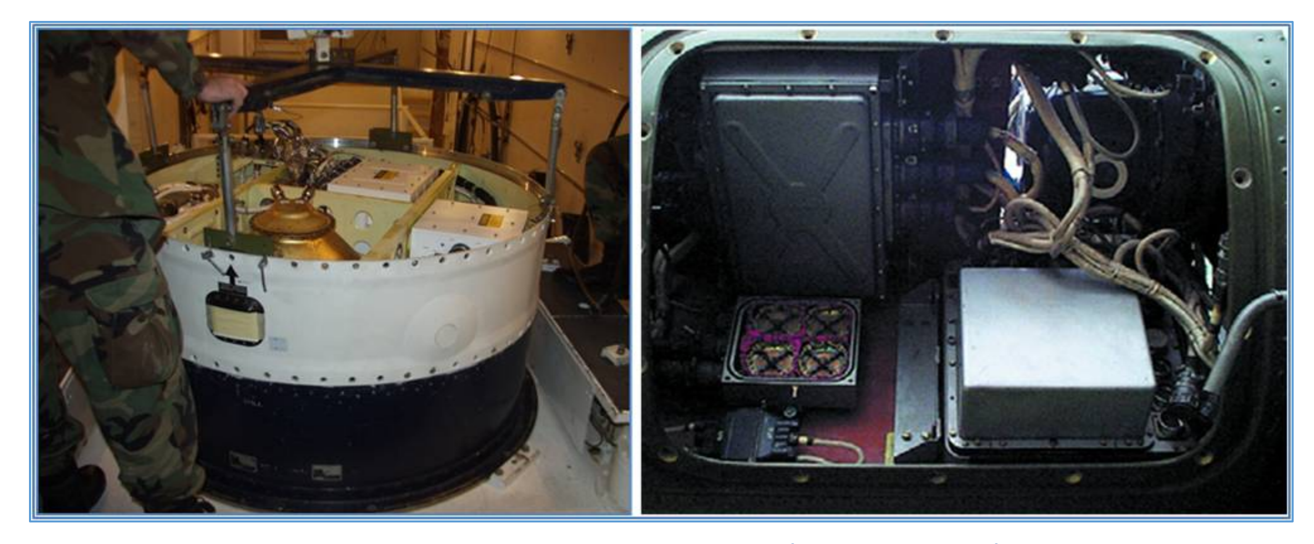


Figure 21: ***Left:*** **A missile guidance set being transported to a launch facility. (Northrop Grumman)** ***Right:*** **An older-technology guidance set, composed several components, installed in a missile. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))**

Typical Missile-Related Uses: A guidance set is a common subsystem for any missile system. Ballistic missile guidance sets are usually very specialized pieces of equipment, often built to fit into a particular missile, to endure hostile environments, and to perform with a high degree of accuracy. They are designed to satisfy the stringent size, weight, power, and harsh environmental requirements of space launch and ballistic missile applications. UAV guidance systems, including those for cruise missiles, can still be highly specialized but less complicated systems, and they are often supplemented with numerous other sensors and receivers as part of an integrated navigation system (detailed in 9.A.).

Other Uses: Guidance and navigation systems of various types are widely used in marine vessels, aircraft, and even some land vehicles.

Appearance (as manufactured): The size, weight, and appearance of guidance sets vary with the type of missile because of the structural features of the missile and variations in mission requirements. Older designs tend to be larger and heavier (up to around 1 m on a side / diameter and weighing up to 100 kg); new systems, which are significantly more accurate, may require only 30 cm on a side and weigh a few kilograms. Most sets are enclosed in metallic boxes that have airtight but removable access panels. They are often rectangular, but they can also be cylindrical or be comprised of several boxes of various shapes (Figure 21 (left)). Guidance sets also have quality electrical connectors, precision-mounting surfaces, and, in some cases, temperature control connections. Some systems have a gimbal-mounted or floated IMU housed in a roughly spherical chamber that bulges out somewhere on the guidance set. Other systems have the IMU separate from the electronics.





Figure 22: ***Left:*** **A guidance and navigation system, designed to meet long-term space mission requirements. (Northrop Grumman)** ***Right:*** **A shipping container for an ICBM guidance system.**

Modern strapdown guidance subsystems are often box-like in appearance. Figure 22 shows a guidance and navigation subsystem with access panel removed. Some modern strapdown guidance subsystems deviate from the box-like shape when the application requires the guidance set to fit into a small space.

Appearance (as packaged): Because most guidance sets are very expensive and sensitive to damage from shock, they are shipped in cushioned containers, some of them specially designed and air-tight, to protect them from moisture. These containers usually have labels requesting careful handling. A wide range of container configurations, including special drums, boxes, and metal suitcases, may be used.

2.A.1.e. Thrust vector control subsystems, usable in the systems specified in 1.A., except as provided in the Note below 2.A.1. for those designed for rocket systems that do not exceed the "range"/"payload" capability of systems specified in 1.A.;

Technical Note:
2.A.1.e. includes the following methods of achieving thrust vector control:
a. Flexible nozzle;
b. Fluid or secondary gas injection;
c. Movable engine or nozzle;
d. Deflection of exhaust gas stream (jet vanes or probes);
e. Use of thrust tabs.

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- North Korea
- Russian Federation
- Serbia
- Spain
- Ukraine
- United Kingdom
- United States

Global Production



Nature and Purpose: Thrust vector control (TVC) subsystems redirect the axial thrust by slightly changing the direction of the hot gases expelled through the rocket nozzle, and thereby steer the missile.

Method of Operation: There are several different ways of steering a missile. Generally, they redirect the engine thrust slightly away from the missile centerline, which causes the vehicle to turn. Export control under this item applies regardless of the specific design or name of the thrust vector control subsystem. Liquid rocket stages usually redirect thrust by swiveling one or more entire engines, a process called gimbaling after the gimbal-type mounts that have rotating bearings on one or more axes. In contrast, most modern solid rocket motors use flexible nozzles. Both approaches use servo-mechanical actuators attached to the missile frame to continuously push and pull the engine or rocket nozzle slightly sideways. Alternatively, steering can be done by deflecting the exhaust gases in fixed rocket nozzles by means of movable jet vanes, or by introducing additional gas or liquid into the nozzle from the side (fluid injection).

Jet vanes are an older technology that requires materials able to withstand extreme temperatures due to continuous immersion in the rocket exhaust. A cooler-running alternative is thrust tabs, which would typically be four paddles that rotate in and out of the hot gas flow at the edge of the nozzle exit. They are mounted beyond the nozzle radius at its exit, with rotation about an axis parallel to the missile. Fluid injection from the side causes the exhaust flow through the nozzle to deflect sideways from the center axis, thereby causing asymmetric flow and an off-centerline direction of thrust.

Another method for missile steering is to place small liquid propellant engines at four points around the main engine. Such Vernier engines are simply turned on and off to steer a missile, much like satellite

attitude control. As in the latter implementation, Vernier engines on a missile may be able to steer the missile to re-orient it during a coast phase, in the absence of thrust from the main nozzle.

Typical Missile-Related Uses: Thrust vector control subsystems change rocket thrust direction to steer the missile in response to commands from the guidance set. They are a required item on space launch vehicles and ballistic missile systems and are used on some UAV systems, particularly cruise missile booster motors.

Other Uses: Different types of thrust vector control subsystems are used in advanced fighter aircraft, research aircraft, and spacecraft.

Appearance (as manufactured): Thrust vector control assemblies may include mounting rings (e.g. gimbals), hydraulic actuator rods, valves, tubing or pipes, and dedicated control electronics. Electromechanical actuators are a more modern alternative to hydraulic ones. An example of a thrust vector control electronics box for a large liquid rocket engine is shown on the left of Figure 12. Mounting rings are attached to the throat area of the nozzle, and are robust enough to withstand the torque imparted under full-thrust conditions. An actuating system is attached to either the mounting ring, the engine itself, or directly to the nozzle.

Hydraulic actuator rods are cylindrical, and may be 15 cm to 45 cm in length and 3 cm to 8 cm in diameter, or otherwise depending on the size of the missile (Figure 23 (right)). They push and pull on the engine or nozzle in response to signals by the guidance system to actuator valves. A gas generator (basically a small solid rocket motor) that powers a small turbopump is one way to pressurize the hydraulic fluid. Similarly, a turbine could drive an electric generator to power electromechanical actuators. Mounting rings and actuator rods are made from high-strength metals such as stainless steel or titanium; actuating valves are likely to have stainless steel housings.





Figure 23: ***Left:*** **A thrust vector control electronics box for use in large launch vehicle applications. (Moog, Inc.)** ***Center:*** **Four jet vanes mounted in the rear of a ballistic missile. (Russian military)** ***Right:*** **A fine positioning linear actuator designed for use in space applications. (Moog, Inc)**

The most common way to implement gas or fluid injection thrust vector control is to store the gas or fluid in tanks and then meter its injection into the rocket nozzle through feedlines, valves, sometimes manifolds, and injectors. The tanks are usually cylindrical composite-overwrapped pressure vessels that vary in size and weight. Pressure ratings of 7 MPa (1,000 psi) are typical. The gas or liquid feedlines (approximately 1 cm in diameter for smaller engines), control valves, and injectors are often made of

stainless steel.

Jet vanes are mounted either at the rear or inside the exhaust nozzle and rotate in response to commands from the missile guidance system to redirect the thrust. They look like small wings usually 30 cm in length and 15 cm in height (sizes vary with engine size). They are made of high-temperature material such as carbon, carbon derivatives, or refractory materials such as tungsten. The center image in Figure 23 shows four jet vanes mounted in the aft end of a ballistic missile. While the vanes are flat panels, their aft edges appear in the image as light-colored lines pointing toward the center axis of the missile.

Appearance (as packaged): Gimbal rings are usually 15 cm to 50 cm in diameter and may be shipped as an assembly (double rings permit two axes of rotation) in an appropriate shipping container to prevent damage. While a single nozzle on a missile stage needs two perpendicular directions of motion, the use of multiple main engines offers the possibility for each to move in only one particular direction, or for some to not move at all if there are many. Actuator rods and valves look like commercial rods and valves. Valves are packaged inside plastic bags for protection against abrasive particles. Because these items can be rather heavy, they are shipped secured in robust containers made of metal or wood. Gas or fluid injection tanks are packaged like commercial products such as propane tanks. Injectors and valves are usually packaged like any piece of expensive equipment in padded containers, and in plastic bags to prevent contamination.

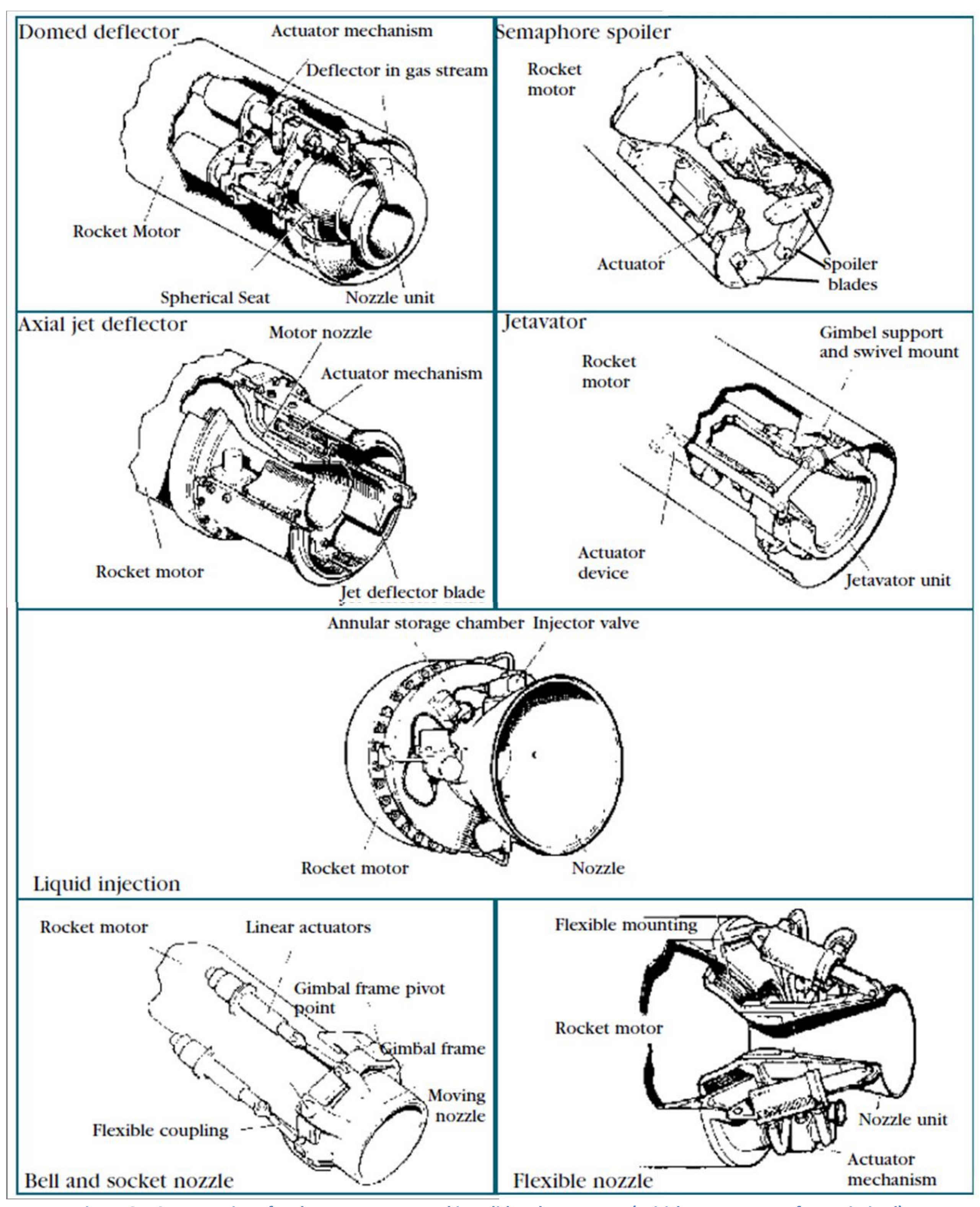


Figure 24: Seven options for thrust vector control in solid rocket motors. (British Aerospace Defense Limited)

2.A.1.f. Weapon or warhead safing, arming, fuzing, and firing mechanisms, usable in the systems specified in 1.A., except as provided in the Note below 2.A.1. for those designed for systems other than those specified in 1.A.

Note:

The exceptions in 2.A.1.b., 2.A.1.d., 2.A.1.e. and 2.A.1.f. above may be treated as Category II if the subsystem is exported subject to end-use statements and quantity limits appropriate for the excepted end-use stated above.

- **For advanced RV fuzing systems**
- China
- France
- Germany
- India
- Israel
- Russian Federation
- United Kingdom
- United States

- **Other types of SAFF components, particularly for air vehicles, are commonly available.**

Global Production



Nature and Purpose: Warhead safing, arming, fuzing, and firing (SAFF) mechanisms are usually electronic or electro-mechanical devices that keep missile payloads (warheads) safely unarmed until shortly before reaching the target, at which time they fuze and fire the explosives.

Method of Operation: Before launch, most SAFF subsystems ensure that the warhead is safe (unable to detonate) by either mechanically or electrically isolating the warhead from the firing system. After launch, the SAFF subsystem removes the interlocks and arms the warhead. Arming can occur after a set time from launch or after sensing a preprogrammed trajectory change or certain environmental conditions such as an expected deceleration. Low technology SAFF subsystems use barometric switches for the safing and arming functions.

The fuze defines when the detonation criteria are met. Common fuzes include timers, acceleration sensors, and altitude sensing devices such as barometric switches or active radars. When the payload reaches the predefined criteria, a signal is generated and sent to the firing set. High voltage capacitors are then fired (discharged) and deliver an electric current to the warhead detonators. Payloads can also have crush or contact fuzes that sense when payloads strike the targets and begin to break up. These fuzes either back up the altitude sensing system or are used for missions requiring target impact. Cruise missiles that air burst their warheads or dispense submunitions will fuze and fire when the guidance system determines that the target has been reached. Alternatively, they can use radar or laser altimeters, proximity fuzes, and contact fuzes. A SAFF subsystem may include some or all of these options for redundancy.





Figure 25: *Left:* An RV SAFF system accelerometer with its associated electronics. *Right:* A missile fuze with safety plate and warning label. (Kaman Aerospace Corporation)

Radar-based fuzing mechanisms for ballistic missiles require a relatively high frequency (S-band or C-band) transmitter and transmissive window materials such as high purity silica to protect the outward-looking antenna from the heat created during re-entry. For missile applications, contact fuzes are rated between 100 g and 500 g. High technology ballistic missile fuzing mechanisms using accelerometers require instruments capable of 100 g or more.

Typical Missile-Related Uses: Some form of SAFF subsystem is required on all missile systems with explosive warheads to ensure that the weapons are safe until launched and detonate when intended. Because SAFF subsystems are usually tailored to the internal configuration and function of a specific missile, it is not cost effective to modify them for non-missile applications.

Other Uses: The basic fuzing and firing technology involved in a missile SAFF subsystem is used in all munitions items with explosive warheads. The more advanced fuzing mechanisms, in which the time or altitude of detonation is determined by active radars or integrating accelerometers, are used in advanced artillery shells and submunitions. The firing technology used for missile warheads is used commercially in all activities in which explosives are used, such as road construction, mine excavations, and structures demolition.



Figure 26: A wooden shipping container with explosives warning label. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))

Appearance (as manufactured): Missile SAFF subsystems and packages are not obtained as a single unit; instead, they are assembled from individual components and subsystems (Figure 25). These components are generally small, aluminum-housed packages with input/output electrical connectors. Simple fuzes are usually housed in aluminum cylinders ranging in diameter from 1 cm for crush fuzes to several centimeters for contact fuzes. Higher technology fuzing mechanisms may involve sophisticated instruments such as

accelerometers or active radar transmitters and antennas.

Note:
The exceptions in 2.A.1.b., 2.A.1.d., 2.A.1.e., and 2.A.1.f. above may be treated as Category II if the subsystem is exported subject to the end-use statements and quantity limits appropriate for the excepted end-use stated above

Appearance (as packaged): Like most electronics, SAFF subsystems are shipped in cushioned containers, some of them special, air-tight containers to protect them from moisture. These containers usually have labels indicating the need for careful handling. A wide range of suitable container configurations, including special drums, boxes, and metal suitcases, may be used. Any of these may in turn be packed in a wooden box (Figure 26) with the explosives warning label (when appropriate) or may be shipped in ordinary cardboard boxes.

2.B. Test and Production Equipment

2.B.1. "Production facilities" specially designed for the subsystems specified in 2.A.

- Argentina
- Brazil
- Canada
- China
- Egypt
- France
- Germany
- India
- Israel
- Italy
- Japan
- Libya
- North Korea
- Norway
- Pakistan
- Russian Federation
- Serbia
- Republic of Korea
- Spain
- Sweden
- Syria
- Ukraine
- United Kingdom
- United States

Global Production



Nature and Purpose: Subsystem production facilities are often large industrial areas designed to manufacture the major assemblies such as solid propellant rocket motors or liquid propellant rocket engines, guidance and control equipment or re-entry vehicles. Overhead cranes are used to move heavy components. Large X-ray equipment may be available to check for voids and cracks in welds or in the missile propellant. Solid propellant mixing facilities are often built in isolated regions, removed from populated areas for both security and safety. Guidance subsystem and re-entry subsystem manufacturing facilities are characterized by clean rooms and filtered-air systems that are usually temperature and humidity controlled. Technicians must wear special clothing to control dust or lint and static electricity. A prime requisite for the manufacture of guidance instrumentation is a rigorous filtration system. Air is passed through high-efficiency particulate absorption (HEPA) filters, often covering the entire ceiling area of the clean room.

Method of Operation: Ballistic missile subassemblies are manufactured and often tested in their production facilities before they are shipped either to storage or to a final assembly area. Raw materials

such as sheet steel are rolled into the proper forms and welded together to form cylinders that will become the solid propellant rocket motor case. End domes are welded onto these cylinders to complete the enclosure. Each end dome has a reinforced circular opening to mount the stage igniter and to attach the nozzle.

The strength of a small number of sample motor cases is tested in special test facilities. Here, a motor case is hydrostatically tested to its burst point to confirm its pressure holding capacity and to validate the manufacturing processes used to build that lot of motor cases. The motor case is sealed, filled with water and pressurized until it bursts. Instruments are attached to the motor case, and the stress and strain are recorded, as is the water pressure during the test. Often the procedure is video recorded to support detailed failure analysis.

Liquid propellant rocket engines are complex mechanical devices that require many precise machining and assembly steps, often in clean rooms. Small precision parts are cast, machined, assembled and cleaned. The larger propellant tank assemblies are commonly manufactured in sheet-forming facilities that roll the sheet material into cylindrical sections that are then welded together along their axial seams. End domes are then welded to the resulting cylinders. These and other welds offer failure points on the missile and must be thoroughly inspected. Nondestructive X-ray or other means are often used to inspect this welding. Overhead cranes are used to move and position these missile components to and from handling jigs.

Accurate guidance subsystem production imposes the greatest demands of all ballistic missile production facilities. Manufacturing high-quality inertial instruments requires a number of highly skilled people. The manufacturing procedures require full attention to the details of close-tolerance miniaturized electromechanical component production. Missile guidance subsystem manufacturing facilities require precision equipment and clean-room conditions to manufacture and test the individual guidance instruments and then assemble them into a guidance subsystem. Hoists and cranes are available to move components to and from handling jigs and shipping containers.

Typical Missile-Related Uses: The components and assemblies manufactured at these facilities are used to build and test items listed in 2.A.

Other Uses: N/A

Appearance (as manufactured): Several individual and specialized facilities are required to produce missile components. Fixtures used in the production of solid propellant rocket motors are usually large and heavy structures. Mixing and casting rocket propellant is hazardous, and the activity is ordinarily completed in isolated locations to minimize the results of an explosion. Large-diameter plumbing and large-capacity pits that may include facilities for drawing a vacuum in the rocket motor may be present. Star or multi-finned shaped mandrels may be visible.

Production facilities for liquid propellant rocket engines may involve smaller structures, but they normally require large-scale test stands. Medium-range ballistic missiles and smaller missiles could be fabricated in

a facility that would look much like any large, well-equipped machine shop. A quality assurance facility is needed with laboratories. These will include clean rooms, air-flow benches, granite surface plates, precision measuring devices including scanning electron microscopes (SEMs), coordinate measuring machines, gas sniffers with a detection capability of less than 5 parts per million and other specialized measurement devices as required. Stations for assembling high-tech re-entry vehicles include clean rooms to insure reliability in the arming and fuzing components and balance tables to configure the center of gravity in the appropriate position. Hoists and cranes are available to move fragile components to and from handling jigs and shipping containers.

Additive Manufacturing (AM) machines can be located almost anywhere. Typical Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) machines are 2.2m x 1.1m x 2.3m, and with all ancillary equipment it can be placed in a room of 5.3m x 4.1m. The room will need environmental controls to hold temperature and relative humidity at required conditions.

Appearance (as packaged): New or replacement spare parts for these types of facilities are sometimes large and too heavy to be packaged and shipped to the production plant as complete units. Instead, component parts are shipped separately in crates or on protected pallets for onsite assembly. They will be securely fastened to the crate to restrain motion and prevent damage. Smaller jigs may be individually crated or secured on pallets for shipment.

2.B.2. "Production equipment" specially designed for the subsystems specified in 2.A.

Nature and Purpose: Production of these subsystems requires equipment tailored to the specific type of subassembly. Each subsystem production facility must contain specialized equipment, jigs, fixtures, molds, dies and mandrels that are used to manufacture the subassembly's components, assemble them and test the subassembly.



Figure 27: A large milling machine. (Yasda Precision Tools, K.K.)

Method of Operation: Equipment used to build solid propellant rocket motors includes metalworking machinery, equipment for sizing or filtering propellant constituents and mixing the propellant, molds or mandrels to form the motor core or burning surface, devices for fabricating and pyrolizing motor nozzles and equipment to test the thrust vector control subsystem on the completed motor. Facilities may also contain winding equipment for covering motor cases with composite fiber materials.

- Argentina
- Brazil
- Canada
- China
- Egypt
- France
- Germany
- India
- Iran
- Israel
- Italy
- Japan
- Libya
- North Korea
- Norway
- Pakistan
- Russian Federation
- Serbia
- Republic of Korea
- Spain
- Sweden
- Syria
- Ukraine
- United Kingdom
- United States

Global Production

Many motor cases can be manufactured from steel. In one method, steel sheets are rolled and welded in order to achieve the size and strength called for by the case's design. Other techniques form the cylindrical portion of the motor by extruding or flow-forming metal over a mandrel. The domes that form the ends of the case are then created by flow-forming or die forming. Extruding and flow-forming steel reduces the number of possible failure points on the finished motor case by reducing the number of welds needed.

Some motor manufacturing facilities contain filament-winding machines that lay strong fibers coated with an epoxy or polyester resin onto rotating mandrels to create composite parts with a high strength-to-weight ratio. After the winding operation is completed, the parts require autoclave and hydroclave curing to finish the process.

The largest and most distinctive equipment in a solid propellant rocket motor production facility is the propellant mixing station. This facility must be large enough to house the propellant ingredients, mixers and other tooling used to make the motor stage. Solid propellant constituents (fuels, oxidizers and other agents) are first reduced in size to appropriate diameters then blended with a suitable binding agent until the mixture (known as the "grain") becomes homogenous. If the mixing process can be completed in a vacuum, the number of bubbles in the grain can be minimized. (Bubbles represent increased burning surfaces that result in pressure spikes and possible motor case failure during combustion.) After the propellant constituents are completely mixed together, the mixture is placed into the motor case. There are three principal methods for loading a motor case with propellant. The propellant can be poured into the case (a process known as "casting the propellant" and sometimes done under vacuum), pumped into the case, or, if the propellant is sufficiently rigid, it may be extruded through a mold and inserted into the case.

Insulating material must be placed between the case wall and the propellant to prevent the case from failing due to the heat of combustion. Insulation is often a thin layer of synthetic rubbery material, such as ethylene propylene diene monomer (EPDM). Special sprayers may apply a thin layer of insulation to the inside of the motor case or a layer of insulating material may be applied to a mandrel over which a composite motor case is wound and cured.

Most nozzles for modern solid propellant rocket motors are manufactured from either bulk graphite or multidimensional carbon-carbon billets. Graphite billets are produced from fine-grain graphite powders, molded under high pressure and temperature into billet form. Carbon-carbon billets begin with woven

carbon fiber preforms, which are repeatedly densified with either coal tar pitch or hydrocarbon gas under very high pressure and temperature. Isostatic presses may be used during this process. The resulting carbon-carbon or graphite billet is then machined to the intended nozzle shape.

Every component in a liquid propellant rocket propulsion subsystem requires production equipment. Propellant on-off valves, for example, require milling machines, like that shown in Figure 27, to manufacture metal parts such as cases, valve seats and pintles. Electromagnetic coils are attached to the pintles, and the valves are assembled in assembly jigs (fixtures) for welding by specialized welding equipment. Other final assembly operations are also performed. Assembled valves go through an array of inspections using specialized equipment to ensure that they meet all the procurement specification requirements. Leak checks require high-pressure helium and a gas chromatograph with capability to at least five parts per million. An automated testing machine is used to perform repetitive actuation of the propellant on-off valves, while fluid is flowing through the valves, to ensure the valves will meet the number of required on-off cycles. Numerous other acceptance tests are completed during production and delivery.

As new manufacturing technologies develop, the way tooling, electronics, and missile components are produced has evolved. Advanced manufacturing techniques continue to mature and are ever changing the environment in which manufacturing takes place. One of the areas maturing the fastest is in Additive Manufacturing (AM). AM, sometimes called "3D printing", has evolved from the prototype of plastics to full production of polymers, plastics, composites, electronics, metals, and ceramics.

Metals/ceramics AM machines produce parts and tooling utilizing a metal/ceramic powder or wire that is melted/sintered utilizing the Powder Bed Fusion (PBF), Directed Energy Deposition (DED) or Hybrid processes. The powders/wire range from non-ferrous metals of aluminum, copper & titanium to ferrous metals of stainless steels to high strength/high temperature alloys of which many are used in missile technology.

As of 2016, the present state of the industry limits part size for the PBF systems to 250 x 250 x325mm but there are a few machines capable of producing parts up to 800 x 400 x 500 mm. The DED systems are capable of additively manufacturing much larger parts up to 5791 x 1219 x 1219mm.

Electro-discharge machining (EDM) is used extensively in the manufacture of injectors for liquid propellant rocket engines. When first developed, the process was controlled by setup fixtures and manual controls. Computer-controlled EDM and CAD/CAM links are now the norm.

After components are tested and delivered to the final assembly area, the propulsion subsystem is assembled and numerous measurements and checks are made to verify that the completed subsystem corresponds to the design. At that point the propulsion subsystem could be tested to verify that it meets requirements.

The equipment used to manufacture inertial guidance equipment is extremely specialized. Special tooling is required to machine the precision castings, bearings, slip rings, torquers and microelectronics that go

into gyroscopes (gyros) and accelerometers. Special equipment is also needed for the precise measurement and inspection of the finished subassemblies. The gyroscope rotor and float case must be precision-machined in order to achieve a uniform wall thickness, smooth surface finish and symmetry. The ball, gas or jewel bearings must also be precision machined. (Stainless steel bearings as small as one-eighth of an inch in diameter, with tolerances in the ten-millionths of an inch, are required for gyroscope rotors.) Further, these inertial instruments use mini- or micro-circuitry to pick off and amplify position information. If any of the manufacturing and finishing procedures are deficient, the entire subsystem will suffer from random torques. Random torques result in drift that affect the precision of the gyro and hence, the accuracy of the guidance subsystem.

Computer-operated test stations and turntables evaluate individual guidance subsystem components for bias, sensitivity and other features inherent in inertial instruments. These measurements are recorded and confirmed with other test stations. These data are also sent as equipment constants to computers that build and test the missile's flight program. Guidance subsystem components are assembled into the final structure in a clean-room environment and tested before shipping to the missile assembly facility or to storage. Once assembled, they are tested to confirm mechanical integrity and ability to operate in the vibration and thermal conditions of launch and flight. These test stations are often included in or positioned near the manufacturing facility and include computer-operated vibration stands, turntables and environmental test chambers.

Equipment specialized to produce re-entry vehicles includes high-temperature ovens and control systems to manufacture the ceramic or ablative material used to protect the RV from the heat associated with re-entering the Earth's atmosphere.

2.C. Materials

None.

2.D. Software

2.D.1. "Software" specially designed or modified for the "use" of "production facilities" specified in 2.B.1.

Nature and Purpose: Automated and computer-assisted manufacturing procedures, including numeric control, are increasingly used to produce missile components rapidly, accurately and with a high degree of repeatability. These procedures require specially designed software.

Method of Operation: Modern machine tools are computer numerically controlled (CNC). A microprocessor in each machine reads the G-Code program that the user creates; it then performs the programmed operations. Personal computers are used to design the parts and are also used to write programs either by manual entry of G-Code or by use of computer-aided manufacturing (CAM) software that creates G-Code from the user's input of cutters and toolpath. CAM generated G-Code programs must be post processed to the specific machine CNC being employed. Generic G-Code generating programs and libraries are available in the public domain.

- Argentina
- Brazil
- Canada
- China
- Egypt
- France
- Germany
- India
- Iran
- Israel
- Italy
- Japan
- Libya
- North Korea
- Norway
- Pakistan
- Russian Federation
- Serbia
- Republic of Korea
- Spain
- Sweden
- Syria
- Ukraine
- United Kingdom
- United States

Global Production

Typical Missile-Related Uses: CNC machine tools are widely used in the manufacturing and testing of missile system parts and rely on both internal software and CAM software to create the various parts of missile systems. Some examples of uses of CNC machine tools to manufacture missile system parts are explained below.

Computer-controlled machine tools and Additive Manufacturing (AM) machines have been used to manufacture liquid propellant rocket engine core main injectors and multi-element pre-burner injectors.

Processes such as diffusion bonding of thin plates use ovens that may be computer-controlled. Plasma spray deposition and other types of material coating such as electroplating are controlled by computer.

Parts of a liquid propellant rocket engine (injectors to chambers and chambers to nozzles) are typically welded, except for those in ground test units. Such "orbital" welding (360 degrees around a cylindrical surface) is presently computer-controlled, requiring specially tailored software.

Inspection of production articles is also increasingly controlled by computer. Injectors, for example, contain hundreds of injector holes whose size, placement and orientation must be verified. Computer-controlled optical comparators are being used to perform this inspection, and specially developed software is required.

Automated equipment is used to control and manage both the flow-forming process used in steel motor case production facilities and the filament-winding machines that lay epoxy– or polyester-resin-coated fibers onto rotating mandrels to create composite motor cases.

CNC lathes and milling machines can be used to turn the specialized graphite or carbon billets into solid propellant motor nozzles and RV nose tips.

Automated machining equipment is required to produce the precision components that make up the inertial guidance instruments. Once these components are assembled, they are tested and their performance is evaluated on computer-operated test stations. The results of this testing produce data that is used to both characterize the instrument, such as drift rate and scale factor, and define guidance subsystem constants in the flight software.

- Argentina
- Australia
- Brazil
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Pakistan
- Russian Federation
- Rep. of Korea
- Sweden
- Ukraine
- United Kingdom
- United States

Global Production



Other Uses: Software that is used to operate equipment that manufactures missile components and subassemblies may also be employed, with modifications, to control products manufactured in the civil and military aviation industries.

Appearance (as manufactured): Typically, software used to produce rocket assemblies takes the form of a computer program stored on printed, optical, magnetic or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents containing missile production control software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network.

2.D.2. "Software" specially designed or modified for the "use" of rocket motors or engines specified in 2.A.1.c.

Nature and Purpose: Software specially designed or modified for use by solid, hybrid or gel propellant rocket motors or liquid propellant rocket engines is generally integrated into the onboard flight computer software and may perform a multitude of tasks. For rocket motors and engines, the software will monitor sensor data for pressures and temperatures etc. and control the sequencing of events, such as motor ignition, engine shut down, gas generator ignition, initiation of propellant flow (numerous valve openings and closings) and other discrete events either in time or in sequence. These events may be initiated either by internal or external signals from the launch facility or mobile launcher, the inertial navigation system,

other sensors or the flight computer. For liquid propellant engines, some aspects of the engine control system may be integrated into the software of the onboard flight computer such as control of combustion chamber pressure or propellant mixing ratio, the latter using sensor measurements of propellant amounts remaining in the tanks. Finally, certain elements of the thrust vector control subsystem may be considered parts of the engine or motor, such as actuators for a gimbaled nozzle, gimbaled engine systems or altitude control thrusters. The software of the onboard flight computer will control these elements of the thrust vector control subsystem. This category also includes specially designed maintenance and diagnostic software that is used to maintain rocket motors and engines. Most software in this category would be used to conduct automated electrical testing, prior to flight.

Method of Operation: The flight program receives signals, such as the launch signal from the launch facility or mobile launcher, and sends the signals in the proper sequence to accomplish the action. For some solid propellant rocket motors this would include the signal necessary to initiate the pyrogenic charge required to ignite the solid propellant grain in the motor case. For some liquid propellant rocket engines, the flight computer would send a signal to initiate a solid propellant gas generator to start the turbine(s) of the turbopump(s) while opening valves to initiate propellant flow into the combustion chamber. All of these functions will be integrated into the flight software that controls all missile functions from launch. The flight computer, through its control system components, issues all commands and signals required to perform a complete flight within the design parameters. While it is theoretically possible to separate the motor or engine control software from the flight computer and software, it is unlikely. Software for maintenance of these motors or engines could be located in the launch facility or mobile launcher software, the onboard ground control software or autonomous diagnostic equipment.

Typical Missile-Related Uses: The solid, hybrid or gel propellant rocket motor or liquid propellant rocket engine control software is usually integrated into the onboard flight software such that seamless control of all missile subsystems is conducted by flight software. Maintenance software can be located in the launch facility or mobile launcher, in the onboard ground control software or in autonomous diagnostic equipment.

Other Uses: N/A

Appearance (as manufactured): Typically, software used for rocket motors or engines takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents containing rocket motor or engine control software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted electronically over a computer network.

2.D.3. "Software", specially designed or modified for the operation or maintenance of 'guidance sets' specified in 2.A.1.d.

Note:
2.D.3. includes "software", specially designed or modified to enhance the performance of 'guidance sets' to achieve or exceed the accuracy specified in 2.A.1.d.

- Argentina
- Australia
- Brazil
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Pakistan
- Portugal
- Russian Federation
- Republic of Korea
- Sweden
- Ukraine
- United States
- United Kingdom

Global Production

Nature and Purpose: On a rocket system, guidance and control instruments are primarily mounted on a stable platform in the guidance section. The stable platform is controlled by the flight computer. Software in the flight computer collects information from instruments mounted on the platform, processes the data, and issues signals to equipment on the platform to maintain its alignment and stability. When the rocket is launched, the flight computer continues to control the orientation of the stable platform throughout flight. It collects accelerometer information and integrates the data to determine speed and position. It also determines deviations from the programmed flight path and issues correction signals to the flight control system.

Method of Operation: Accelerometers and gyroscopes mounted on the stable platform of a rocket system constantly sense acceleration due to local gravity and the torquing forces caused by the rotating Earth. These forces tend to make the platform wander unless corrected. Flight computer software collects and processes the response data from each gyroscope, incorporating information about individual instruments such as bias, drift rates and offset, and issues signals to torquing motors mounted in the gimbals to keep the platform stable with respect to a rotating Earth. When the rocket is launched, the flight computer continues to control the orientation of the stable platform throughout flight. It collects changing accelerometer data during launch and throughout powered flight and integrates the data to determine speed and position. While the flight computer performs these calculations, it determines sensed deviations from the programmed flight path and issues correction signals to the flight control system. When the computer determines the velocity is proper and the rocket is in the correct altitude, it issues a number of closely spaced commands to terminate thrust and (on some systems) to separate the re-entry vehicle.

UAV guidance subsystems, including those for cruise missiles, may use integrated navigation systems to augment inertial systems to accurately fly to the target. The outputs of these systems are integrated in the flight computer to produce highly accurate navigation. As the flight computer determines deviations from the flight path, it issues correction of steering commands to the flight control system to maintain a proper flight path and altitude.

Typical Missile Related Uses: This software is used to operate and maintain the UAV or rocket system during flight to its target.

Other Uses: Software in this category has few uses that are not related to missiles but may be employed in the military aircraft industry to improve aircraft guidance systems.

Appearance (as manufactured): Typically this software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

2.D.4. "Software" specially designed or modified for the opetation or maintenance of subsystems or equipment specified in 2.A.1.b.3.

- Argentina
- Australia
- Brazil
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Pakistan
- Portugal
- Russian Federation
- Republic of Korea
- Sweden
- Ukraine
- United Kingdom
- United States



Nature and Purpose: Software in the RV is used to monitor the safing, arming, fuzing and firing (SAFF) subsystem and to integrate specialized terminal navigation systems designed to increase the accuracy of the RV.

Method of Operation: The payload contained in a missile RV is designed to activate (detonate, open, disperse sub-munitions, etc.) only after the SAFF mechanism has determined that specific safety constraints have been satisfied. These constraints include receipt of timing, acceleration, deceleration, and barometric signals, computer-generated signals related to the sensed accuracy of the missile to the programmed trajectory, and others determined by the designers. The computer in the RV also operates a terminal guidance system, if available, to precisely steer the RV to its target using a number of radars, sensors and guidance subsystem components configured in an integrated navigation system.

Some weapons activate with the appropriate radar return signal. The radar subsystem must be tested on test benches to confirm its operational reliability. Complete RV subsystems are tested and evaluated during a series of flight and ground tests. Telemetry systems installed in the RV supply subsystem operating performance data to ground stations. Software is used to test these telemetry systems prior to a flight test to verify the confidence of their operability.

Typical Missile Related Uses: This software is employed to collect information from integrated navigation systems within the RV, and to operate terminal guidance systems and the re-entry vehicle SAFF mechanisms.

Other Uses: N/A

Appearance (as manufactured): Typically this software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network.

2.D.5. "Software" specially designed or modified for the operation or maintenance of subsystems in 2.A.1.e.

- Argentina
- Australia
- Brazil
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Pakistan
- Portugal
- Russian Federation
- Republic of Korea
- Sweden
- Ukraine
- United Kingdom
- United Staes

Global Production

Nature and Purpose: This software is used to operate the thrust vector control (TVC) subsystems used to control the trajectory of a ballistic missile and some cruise missiles during boost.

Method of Operation: The trajectory of a ballistic missile is controlled using the thrust vector control subsystems. The flight computer issues corrections or steering signals to the TVC subsystem to move an actuator connected to a liquid propellant rocket engine, a solid propellant missile motor nozzle, a liquid injected thrust vector control device, jet vanes or another device to deflect the thrust. Once the actuator has moved, rate and distance information from the TVC position sensor is sent back to the computer as a feedback signal which is then used to modify the correction or steering command. Thrust vector control software is almost an indistinguishable part of the on-board flight program.

Typical Missile Related Uses: This software is used to operate the thrust vector control subsystems used on ballistic missiles and some cruise missiles.

Other Uses: Similar software may also be used in the civil and military aircraft industry. Airfoil control surfaces use servoactuators and position indicators similar to those used on ballistic missiles.

Appearance (as manufactured): Typically, software used to operate thrust vector control subsystems takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network.

2.D.6. "Software" specially designed or modified for the operation or maintenance of systems in 2.A.1.f.

Note:
Subject to end-use statements appropriate for the excepted end-use, "software" controlled by 2.D.2. - 2.D.6. may be treated as Category II as follows:
1. Under 2.D.2. if specially designed or modified for liquid propellant apogee engines, designed or modified for satellite applications as specified in the Note to 2.A.1.c.;
2. Under 2.D.3. if designed for missiles with a "range" of under 300 km or manned aircraft;
3. Under 2.D.4. if specially designed or modified for re-entry vehicles designed for non-weapon payloads;
4. Under 2.D.5. if designed for rocket systems that do not exceed the "range" "payload" capability of systems specified in 1.A.;
5. Under 2.D.6. if designed for systems other than those specified in 1.A.

- Argentina
- Australia
- Brazil
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Pakistan
- Portugal
- Russian Federation
- Republic of Korea
- Sweden
- Ukraine
- United Kingdom
- United States

Global Production



Nature and Purpose: Software in the RV is used to monitor the safing, arming, fuzing and firing (SAFF) subsystem, located in the RV.

Method of Operation: The payload contained in a missile re-entry vehicle is designed to activate (detonate, open, disperse submunitions, etc.) only after the SAFF mechanism has received data and determined specific safety constraints have been satisfied. These constraints include receipt of timing, acceleration, deceleration, and barometric signals, computer-generated signals related to the sensed accuracy of the missile to the programmed trajectory, and others determined by the designers.

Typical Missile-Related Uses: This software is used to maintain the safety of the re-entry vehicle and the payload stored within.

Other Uses: N/A.

Appearance (as manufactured): Typically this software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network.

Liquid propellant rocket apogee engines designed or modified for the purpose of providing the final burn for a satellite to place it into a predetermined orbit are always pressure-fed. In other words, turbopumps are not used because it is more cost-effective to pressurize relatively small propellant tanks using a high pressure helium bottle. At the subsystem level, software for use of the liquid apogee propulsion subsystem includes a trajectory simulation program; typically, such a computer code would simulate motion in three dimensions with six degrees of freedom. Standard codes of this type can be used for any missile or space launch vehicle of any size, and a number of them are in the public domain. Ones that have been adopted for specific apogee engines or station-keeping engines must be evaluated in the light of the subsystem for which they were tailored.

2.E. Technology

2.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or "software" specified in 2.A., 2.B. or 2.D.

Nature and Purpose: Technology controlled under Item 2.E.1. covers the instructions and knowledge needed to develop, produce or use any of the equipment or software specified in 2.A., 2.B. or 2.D.

Method of Operation: Technical assistance is available in many forms. Technical assistance may consist of instruction provided by a person experienced in one or more controlled subjects (such as liquid propellant rocket engines) who acts as a trainer in a classroom on or near the production site. A country may receive technical assistance from one or more consulting services who specialize in a controlled process or who assist in procuring components or materials that are difficult to obtain. Additionally, a country may receive technical assistance by sending students to other countries that possess the required technology so they may learn and practice the skills necessary to build the required subsystems. Any manuals and materials received during training may qualify as technical data.

Typical Missile-Related Uses: With limited exceptions, technical assistance required to build ballistic missile systems is used only for that purpose. As noted earlier, sounding rockets used in weather research, with minor adjustments, can be converted to ballistic missiles. The "technology" used in each device is very similar.

Other Uses: N/A

Appearance (as manufactured): N/A

Appearance (as packaged): N/A

Category II - Item 3

Propulsion Components and Equipment

Category II – Item 3: Propulsion Components and Equipment

3.A. Equipment, Assemblies and Components

3.A.1. Turbojet and turbofan engines, as follows:

a. Engines having both of the following characteristics:

1. 'Maximum thrust value' greater than 400 N (achieved un-installed) excluding civil certified engines with a 'maximum thrust value' greater than 8.89 kN (achieved un-installed); and
2. Specific fuel consumption of 0.15 kg N^{-1} h^{-1} or less (at maximum continuous power at sea level static conditions using the ICAO standard atmosphere);

Technical Note:

in 3.A.1.a.1., 'maximum thrust value' is the manufacturer's demonstrated maximum thrust for the engine type un-installed. The civil type certified thrust value will be equal to or less than the manufacturer's demonstrated maximum thrust for the engine type.

b. Engines designed or modified for systems specified in 1.A. or 19.A.2., regardless of thrust or specific fuel consumption.

Note:

Engines specified in 3.A.1. may be exported as part of a manned aircraft or in quantities appropriate for replacement parts for a manned aircraft.

- China
- Czech Republic
- Germany
- Israel
- Russian Federation
- Sweden
- United States
- France
- Ukraine
- India
- Japan
- South Africa
- United Kingdom

Global Production



Nature and Purpose: Turbojet and turbofan engines controlled by 3.A.1. are those that can power unmanned aerial vehicles (UAVs), including cruise missiles, great distances. They are similar in design and operation to engines that power civilian aircraft, just smaller in size and power. They make long-range cruise missiles operationally practical.

Method of Operation: Gas turbine engines[1] have several subcomponents, including the fan (in the case of a turbofan), compressor, combustion chamber, and turbine. The compressor, which may consist of one or more stages of alternating stationary and rotating airfoil-section blades, draws air in, pressurizes it, and delivers it into the

[1] The term 'gas turbine' may be used interchangeably with 'turbojet' or 'turbofan' throughout this section.

combustion chamber. The combustion chamber is a heat-resistant tube in which air is mixed with vaporized fuel and then ignited. Spark plugs (called ignitors) initiate combustion, which is continuous once ignition has occurred. The combustion products, or exhaust gases, then pass into the turbine, which consists of one or more stages of alternating stationary and rotating airfoil-section blades. The turbine extracts only enough energy from the gas stream to drive the compressor; the remaining energy provides the thrust. The gas flow then passes into a converging duct, or nozzle, in order to maximize the thrust produced by the engine. In the case of a turbofan engine, there is a larger diameter multiblade fan stage in front of the compressor. Turbofan engines typically have higher thrust and better fuel efficiency than turbojet engines.

Typical Missile-Related Uses: These engines are used to power UAV systems, including cruise missiles.

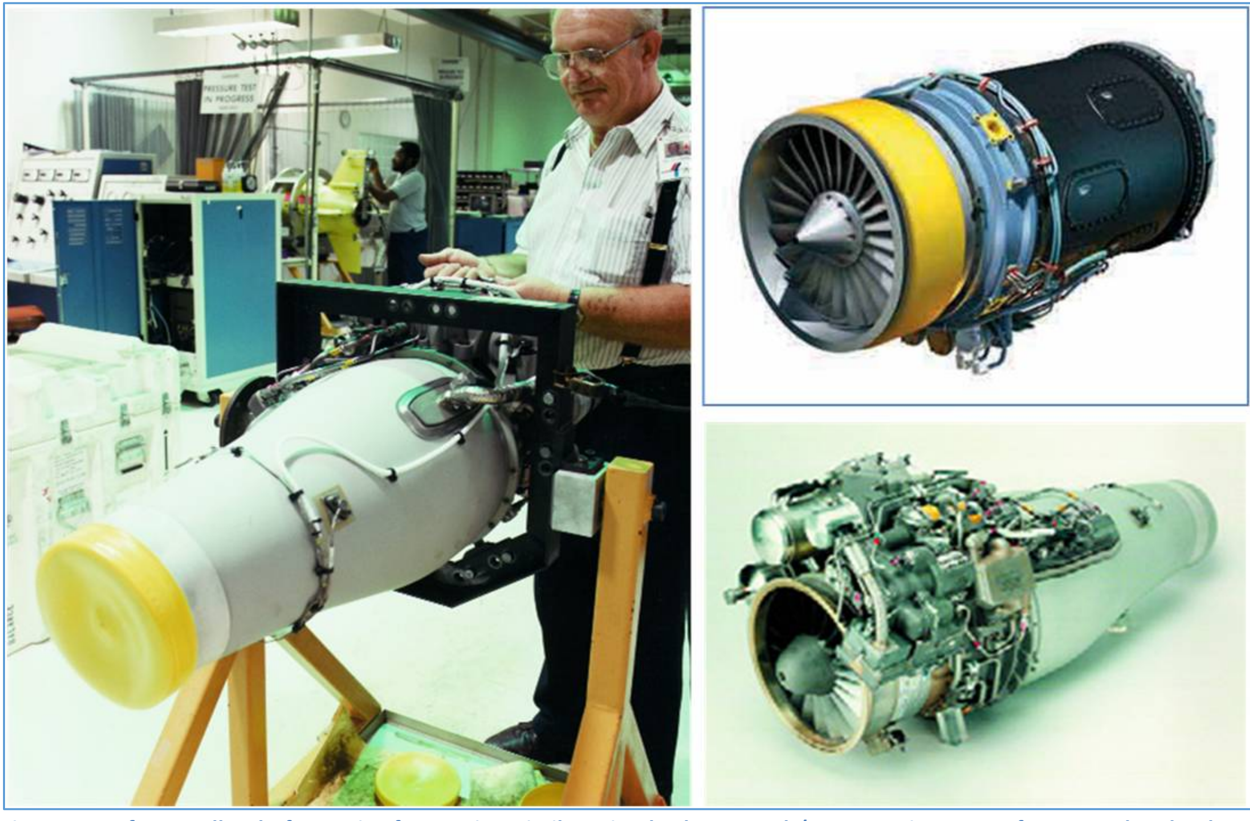


Figure 28: ***Left:*** **A small turbofan engine for a cruise missile on its checkout stand. (MTCR Equipment, Software, and Technology Annex Handbook, Third Edition (May 2005))** ***Top right:*** **A turbofan used to power a HALE UAV. (Rolls Royce Group, plc)** ***Bottom right:*** **A small turbofan engine for a cruise missile. (Williams International)**

Other Uses: Such engines are generally not uniquely designed for cruise missile and other UAV purposes and can be used directly in other applications such as manned aircraft and helicopters. Gas turbine engines are also used in the marine and power-generating industries and in some land vehicles. Marine derivatives of turbine engines power naval and civilian vessels.

Appearance (as manufactured): The typical small gas turbine engine is cylindrical and measures less than 1 m in length and 0.5 m in diameter. Numerous accessories such as an alternator, hydraulic pump, fuel pump, and metering valve, along with associated plumbing and wiring, are visible on the outside of the

engine. Small fuel efficient engines typically weigh 30 kg to 130 kg; larger engines, such as that shown in Figure 28 (top right), have diameters of around 1 m and are 3 m in length. Engine parts are manufactured from a number of different materials, both metallic and non-metallic in composition. Common metallic materials include aluminum, steel, titanium, and special alloys. Non-metallic materials such as Teflon, nylon, carbon, and rubber are used for sealing and insulation.

Appearance (as packaged): Engines usually are prepared for shipment in a multi-step process. Covering plates are attached over the engine inlet and exhaust, and secured by adhesive tape. The engine is covered with protective paper, and desiccant bags are taped to the engine wrap (Figure 29). The engine is wrapped in corrugated cardboard, inserted into a polyethylene bag, lowered into the shipping crate, and rested on foam blocks. The box is then filled with foam and sealed. Because cruise missile engines often incorporate self-starting features through the use of pyrotechnic cartridges, when properly packaged their shipping containers usually bear markings indicating the presence of explosives.



Figure 29: ***Left:*** **A turbojet shipping crate showing the explosive warning labels required because of the starting cartridge. (Teledyne Ryan Aeronautical)** ***Center:*** **A small turbofan engine wrapped in plastic inside its shipping crate. (Teledyne Ryan Aeronautical)** ***Right:*** **A small turbojet engine being prepared for shipment. (Teledyne Ryan Aeronautical)**

3.A.2. Ramjet/scramjet/pulsejet/'combined cycle engines', including devices to regulate combustion, and specially designed components therefor, usable in the systems specified in 1.A. or 19.A.2.

Technical Note:

In Item 3.A.2., 'combined cycle engines' are the engines that employ two or more cycles of the following types of engines: gas-turbine engine (turbojet, turboprop, turbofan and turboshaft), ramjet, scramjet, pulse jet, pulse detonation engine, rocket motor (liquid/solid-propellant and hybrid).

Nature and Purpose: Ramjet, scramjet, and pulsejet engines are internal combustion reaction jet engines that burn fuel mixed with intake air and expel a jet of hot exhaust gases to propel aerial vehicles, including cruise missiles. Because these engines have very few moving parts (they have no mechanical compressors), they are much simpler and potentially less costly than turbojet or turbofan engines. Since ramjets and scramjets can tolerate much higher combustion temperatures than turbojet and turbofan engines, they are the only practical option for sustained flight at high supersonic speeds. Combined cycle engines integrate two propulsion systems (e.g., turbojet and ramjet or scramjet) into a single assembly in order to be operable from rest through supersonic speeds. A pulsejet is another type of compressor-less

jet engine; however, unlike ramjets, combustion takes place intermittently (in pulses), and they can produce thrust at rest.

Method of Operation: Ramjets capture air and direct it into the engine as they move through the atmosphere. The air is compressed by the "ram effect" and slowed to subsonic speeds by diffusion inside the inlet duct. Fuel is added, and the mixture is ignited. Thrust is produced by the expulsion of hot exhaust gases through a nozzle. Ramjets usually operate between Mach 2 and 3, but can operate over a wide range of speeds from high subsonic Mach numbers to supersonic speeds up to about Mach 4. The primary disadvantage of ramjets is that they cannot generate thrust at zero flight speed so they must be accelerated by some other form of propulsion to the necessary starting speed, typically 650 km per hour or higher. A small solid propellant rocket motor is often used at launch for this purpose and discarded after the ramjet/scramjet is started.

"Scramjet" is a contraction of "supersonic combustion ramjet." It operates like the ramjet, but the air entering the engine is not slowed as much and combustion occurs while the air in the engine is supersonic. Scramjets usually operate at speeds between Mach 5 and 7. Scramjets must be boosted to an appropriate speed (over Mach 4) to permit ignition.

A pulsejet produces thrust by a series of explosions occurring at the approximate resonance frequency of the engine. In one design, air is drawn in through open valves at the front of the engine and is heated by the injected burning fuel. The burning gases expand; as they increase the pressure, they close the inlet valves and escape as a jet through the exhaust duct. As the exhaust gases are expelled, the pressure in the combustion chamber decreases, allowing the front intake valves to open again, then the cycle



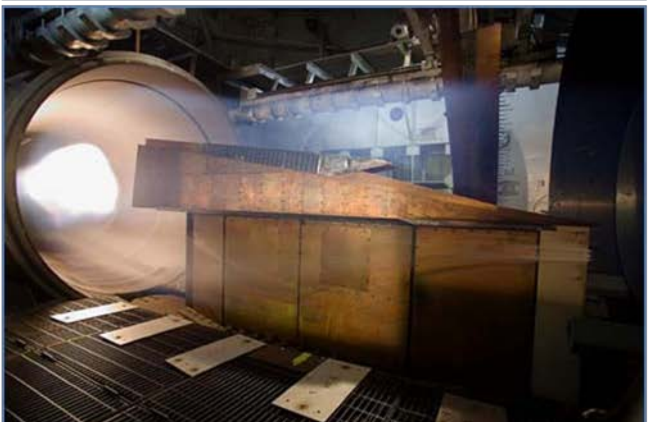
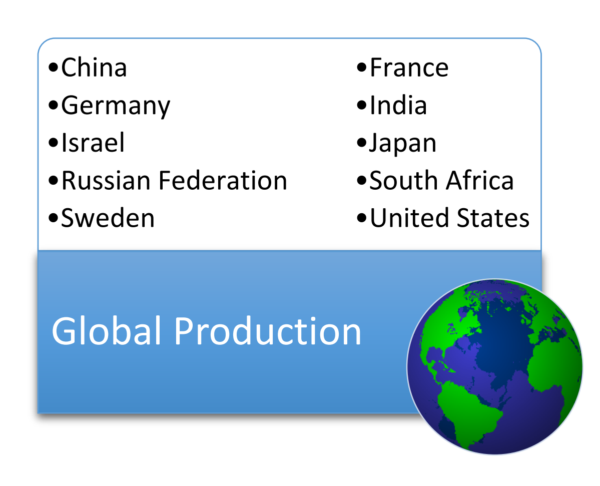




Figure 30: ***Top:*** **A large ramjet engine. (March Field Air Museum)** ***Middle:*** **A scramjet engine completes a Mach 5 test at a wind tunnel facility. (Pratt & Whitney / NASA)** ***Bottom:*** **A modern pulsejet engine with a rearward facing intake. (Thermojet)**



repeats. The function of the intake valves is to prevent flow reversal at the inlet. However, the prevention of flow reversal can be accomplished without the use of valves, through the proper use of inlet duct area design and an understanding of wave phenomena. By extending the length of the inlet duct or by using flow rectifiers (i.e., passages of lesser resistance to the flow in one direction than in the opposite direction), the effects of flow reversal can be inhibited. Some valveless pulsejet configurations also conserve thrust by turning the intake duct 180 degrees to the freestream (facing aft instead of forward). Pulsejets typically operate at subsonic speeds.

The turbojet/ramjet combined cycle engine operates as an afterburning turbojet until it reaches a high Mach speed, at which point airflow is bypassed around the compressor and into the afterburner. The engine then operates as a ramjet with the afterburner acting as the ramjet combustor.

Typical Missile-Related Uses: These engines can be used to power cruise missiles and other types of UAVs. Ramjet and combined cycle engines provide increased speed and performance over turbojet and turbofan engines with minimum volume and weight; however, they are not particularly fuel efficient. Ramjets produce substantially more power per unit volume and typically offer much greater range and/or payload capacity than solid rocket motors. Pulsejets have relatively poor performance and low fuel efficiency, but they are relatively easy to design and manufacture.

Other Uses: Ramjet and combined cycle (turbo-ramjet) engines have been used to power high-speed manned aircraft.

Appearance (as manufactured): Ramjets can be either mounted in cylindrical pods attached to the missile in various locations or built into the missile body. These engines often resemble a metallic pipe with a conical plug in the inlet to control the air flow and a flared conical nozzle on the opposite end. A typical ramjet for missile use can measure 2 m to 4.5 m in length and 0.3 m to 1.0 m in diameter, and weigh up to 200 kg. An example of a relatively large ramjet is shown in Figure 30 (top). A scramjet may look like a simple metallic box with sharp inlets; a scramjet under development to power an air-launched missile is shown in Figure 30 (middle). Pulsejets are characterized by their long cylindrical resonator cavity connected to a bulbous control mechanism towards the front.

Appearance (as packaged): These engines are packaged like turbojet and turbofan engines covered in 3.A.1. above; however, they are most likely to be shipped in wooden or metal crates.

Devices to Regulate Combustion in Ramjets, Scramjets, Pulsejets, and Combined Cycle Engines

Nature and Purpose: Ramjets, scramjets, pulsejets, and combined cycle engines are often required to work over a wide range of velocities, some of which may degrade engine performance. Devices that

regulate combustion by altering air- and fuel-flow characteristics in flight are typically integrated into the engine. The essential elements of a system to regulate ramjets are flow dividers, fuel-injection systems, ignitors, flame holding devices, and a power control computer.

Method of Operation: The control system for a ramjet engine performs two basic functions: it maintains the desired engine performance throughout the flight of the vehicle; and it minimizes departure from the desired performance during transients.

Typical Missile-Related Uses: Devices that regulate combustion can make these engines operate efficiently throughout their flight and thereby increase missile speed and range. These devices are usually specific to the engine application and missile configuration for which they are designed.

Other Uses: The flow dividers, fuel injection and metering devices, and flame holders found in ramjets are similar in concept to devices found in afterburning turbojets and turbofans. However, the devices are not interchangeable.

Appearance (as manufactured): Flow straightening devices such as flow dividers, splitter plates, turning vanes, screens, or aerodynamic grids (Figure 31) minimize airflow distortion and its adverse effects on fuel distribution and combustion.

The fuel used in ramjets is fed to the combustion section with the assistance of a pump and varied through the use of metering devices such as orifices or valves. Fuel injectors disperse the fuel into the air in the combustion section. Ramjet engines require a fuel control (computer) to determine the proper position of the fuel flow metering devices as a function of flight condition. These systems are usually hydro-mechanical or, increasingly, electronic devices.

Ignitors for ramjets take one of several forms. Ramjets may use electrical spark, pyrotechnics, pyrophoric, or hypergolic (self-igniting) liquid injectors. Hypergolic liquids are injected into the stagnant region downstream of the flame holder. Surplus quantities of the ignitor liquid may be carried to enable multiple restarts. Flame holders are used as a means to stabilize the flame produced by combustion and to promote additional combustion. The flame holder is designed to provide a low-velocity region to which the hot combustion products are recirculated to the flame holder. These hot gases then serve as the means for igniting the fresh fuel-air mixture as it flows past the baffle.



Figure 31: ***Left:*** **A fuel manifold and centrifugal fuel injector assembly for a ramjet engine. (Kaiser Marquardt)** ***Center*****: Various aerodynamic grids used to straighten the flow of air into a ramjet engine. (Kaiser Marquardt)** ***Right*****: A fuel management system for a ramjet engine. (Kaiser Marquardt)**

Appearance (as packaged): Aerodynamic grids, combustors, and flame holders are integral to the ramjet and thus are shipped together with the main engine. The exceptions are the fuel pumps, ignitors, or fuel controls, which may be shipped separately and then mounted on the engine body during assembly. These parts are shipped in wooden or cardboard containers.

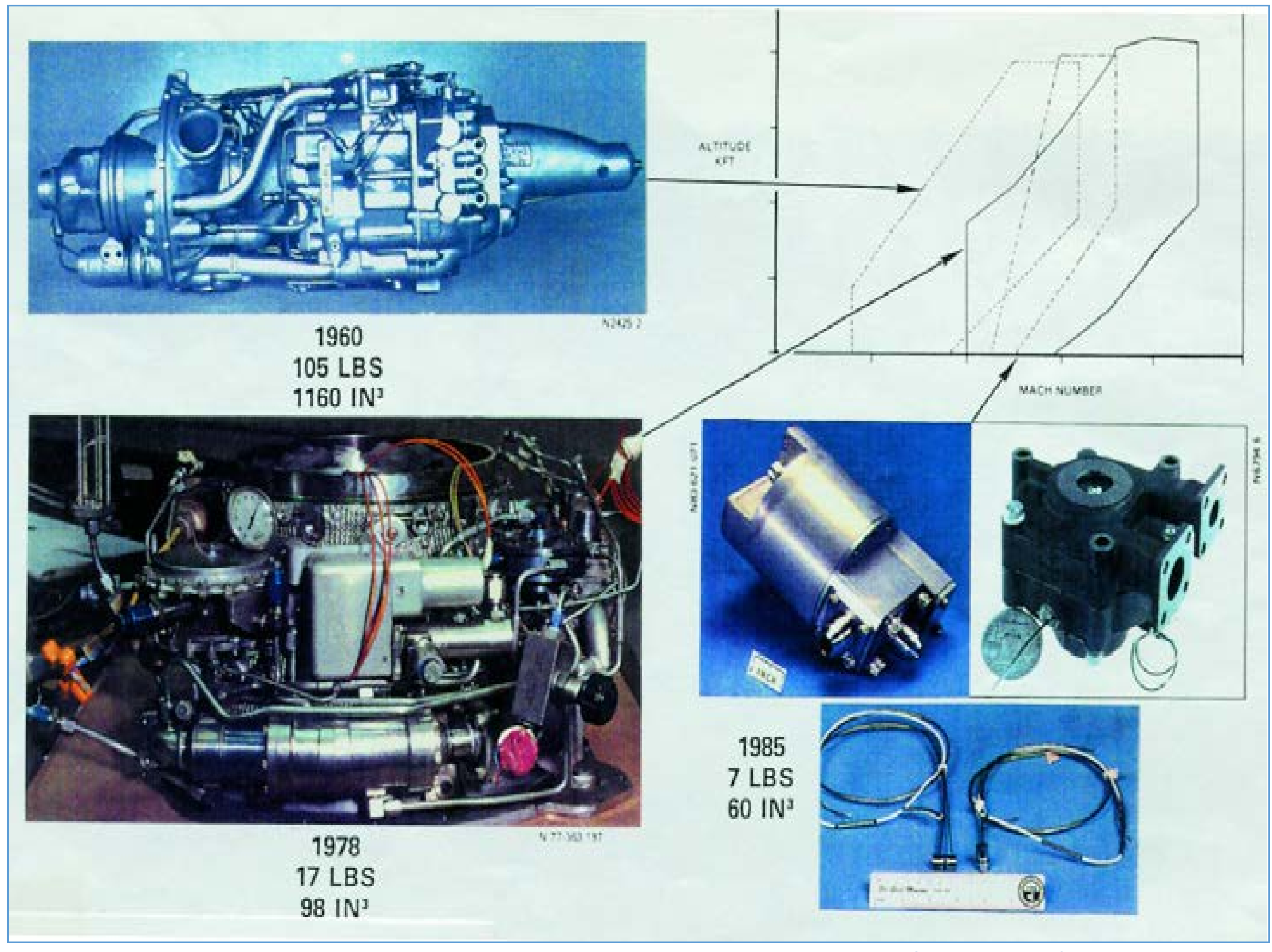


Figure 32: Ramjet fuel control technology has progressed significantly since the 1960's. (Kaiser Marquardt)

3.A.3. Rocket motor cases, 'insulation' components and nozzles therefor, usable in the subsystems specified in 2.A.1.c.1. or 20.A.1.b.1.

Technical Note:
In 3.A.3. ´insulation´ intended to be applied to the components of a rocket motor, i.e. the case, nozzle inlets, case closures, includes cured or semi-cured compounded rubber components comprising sheet stock containing an insulating or refractory material. It may also be incorporated as stress relief boots or flaps.

Note:
Refer to 3.C.2. for 'insulation' material in bulk or sheet form.

- Brazil
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Norway
- Russian Federation
- South Africa
- Sweden
- Ukraine
- United Kingdom
- United States

Global Production



Nature and Purpose: Rocket motor cases are the main structural components of solid or hybrid rocket motors. Cases are the cylindrical containers of the propellant. They use special materials to resist the pressures and heat of combustion.

Rocket nozzles are flow constrictors with bell-shaped structures fitted to the exhaust end of a solid propellant rocket motor or a hybrid rocket motor. Their design controls the flow of hot exhaust gases to maximize velocity in the desired direction and thereby improve thrust.

Method of Operation: Rocket motor cases are pressure vessels used to contain the hot gases generated by the propellant combustion process. During missile launch and flight, burning propellants create a large quantity of combustion gases. These hot gases are expanded and accelerated through the rocket motor nozzle to produce thrust. Interior lining and insulation are low-density, high-heat-resistant materials that provide protective layers between the burning propellant and the case.

Typical Missile-Related Uses: All solid propellant rocket motors use motor cases and interior lining or insulation. Such cases are usually designed to meet specific requirements of particular missiles. Cases, interior lining, and insulation are critical to maintain the integrity of solid rocket motors.

Rocket nozzles manage combustion gases to ensure efficient rocket operation. Well-designed rocket nozzles improve range capability. Nozzles are used on large individual rocket motor stages that supply the main thrust for a ballistic missile; on the small control motors that steer, separate, or spin the missile along its flight path; and on booster rockets that launch UAVs, including cruise missiles.

Other Uses: Motor case materials are used in high-pressure applications such as piping. Some materials used in the interior linings or insulation of rocket motors are used in military or commercial applications requiring heat-resistant materials. Rocket motors (and hence nozzles) have been used to propel experimental manned aircraft such as the X-1 and X-15 research airplanes.



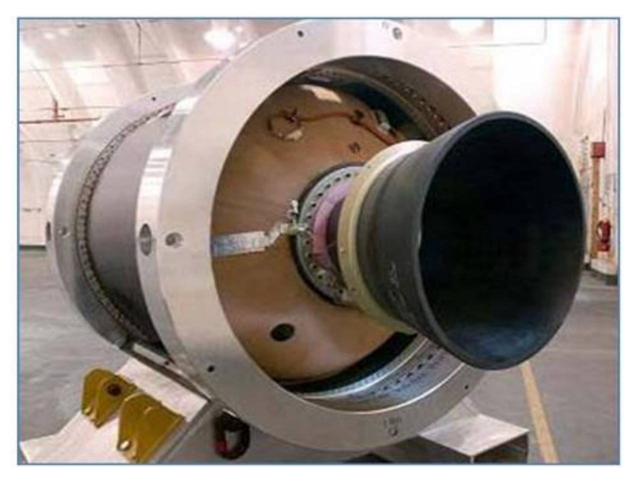


Figure 33: *Left:* A selection of composite rocket motor cases designed to support a range of mission platforms, including the first, second and third stage rocket stages of a space launch vehicle. (ATK) *Right:* A rocket motor – installed in a case – which functions as the third-stage of a launch vehicle. (ATK)

Appearance (as manufactured): A rocket motor case is a large, steel or composite-filament-wound cylinder with spheroidal or ellipsoidal domes at both ends. A motor case for an Item 2.A.1.c. rocket motor typically would be larger than 4 m in length and 0.5 m in diameter. Each of the domes usually has a hole; the small hole at the front end is for the igniter, and the large hole at the back end is for the nozzle. A selection of rocket motor cases displaying these features is shown in Figure 33. An interior lining is a thin coating of special chemicals used to help the solid propellant adhere to the case insulation. This lining is usually applied to the case before propellant casting.

The case may or may not have internal insulation in place when shipped. Rocket motor insulation is usually made of synthetic rubbery material such as ethylene propylene diene monomer (EPDM), polybutadiene, neoprene, or nitrile rubber. Insulation material contains silica or asbestos and resembles a gray or green sheet of rubber approximately 2 mm to 6 mm thick.

The shape of a rocket nozzle is either similar to an hourglass (convergent-divergent) or conical extending rearward from the narrow throat section at the aft end of the solid rocket motor.

Figure 34 shows a cut-away view of a solid propellant rocket motor and where the nozzle fits into the aft end of the motor. Modern solid propellant rocket motor nozzles are almost always made from carbon-composite materials or combinations of carbon-composite and silica phenolic materials. Carbon-composite sections are generally black; phenolic sections are often yellowish in color.

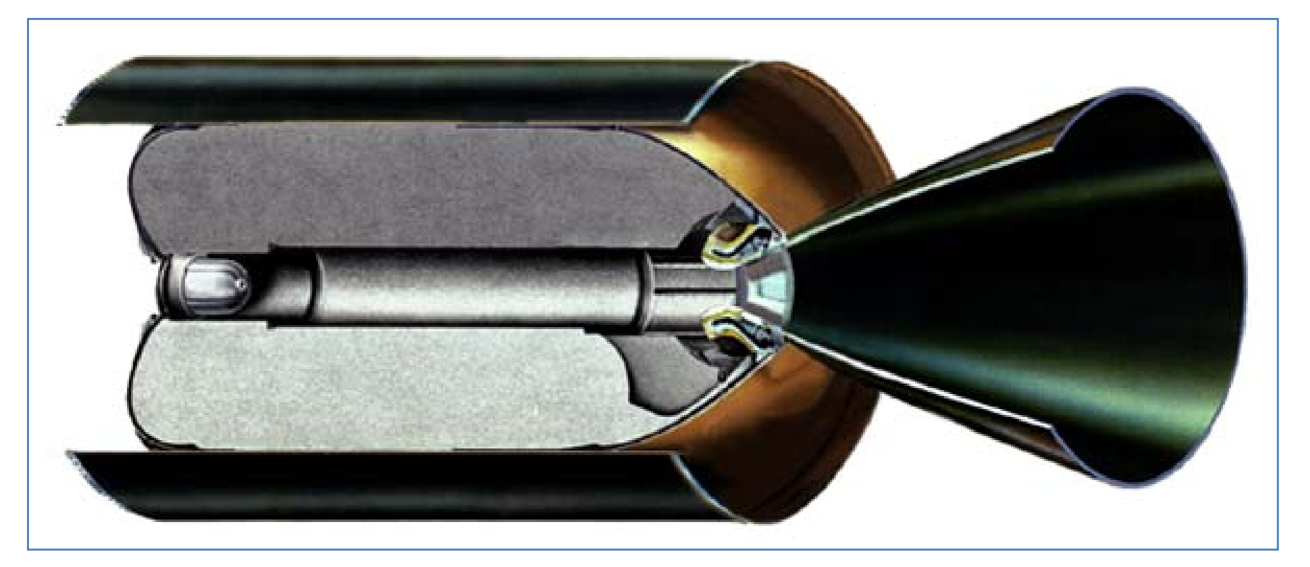


Figure 34: A cut-away view of a solid propellant rocket motor showing where the rocket nozzle is inserted. Also pictured is the ignitor at the top of the motor. (Aerojet)

Nozzle size depends on the rocket size and application. Large nozzles intended for solid propellant rocket motors are increasingly built as movable nozzles. In such an application, the forward end of the nozzle has devices and insulators that allow it to be attached to the aft dome of the motor in a ball-in-socket arrangement. These nozzles may have 2 to 4 lugs on the outside wall to which the motion actuators are fastened, or the actuators may be connected near the throat. Very advanced nozzles can be extendable, which means they are stored in a collapsed configuration and extended to their full dimensions when needed.



Figure 35: A rocket motor with a large fixed, canted nozzle. The motor is used on a launch vehicle. (ATK)

Appearance (as packaged): Rocket motor cases (Figure 36) are shipped in large wooden or metal crates that contain foam packing or other material to protect them from shock during shipment. Insulation material is shipped on large rolls up to 1 m in width and 0.5 m in diameter and sealed in boxes.



Figure 36: L*eft*: Installation of insulation inside a filament wound rocket motor case. (Thiokol Corp.) R*ight*: A rocket motor case under inspection after application of the thermal insulation. (Fiat Avio)

Shipping containers for rocket nozzles are of two types, depending on nozzle size. Small nozzles with an exit diameter no greater than 50 cm have tailored containers, even metallic cases. Larger nozzles usually have tailored shipping containers built from wood or fiberglass. Protective plastic wraps may also be used, depending on the environmental control capability of the shipping container.

3.A.4. sepas, separation mechanisms, and interstages therefor, usable in the systems specified in 1.A.

Note:

See also Item 11.A.5.

Technical Note:

Staging and separation mechanisms specified in 3.A.4. may contain some of the following components:

- Pyrotechnic bolts, nuts and shackles;
- Ball locks;
- Circular cutting devices;
- Flexible linear shaped charges (FLSC).

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- North Korea
- Russian Federation
- United Kingdom
- United States

Global Production



Nature and Purpose: Staging mechanisms ensure the safe and reliable separation of two missile stages after termination of the thrust of the lower stage. This separation is achieved by relatively simple separation mechanisms, the most common of which are explosive bolts and flexible linear shaped charges (FLSC). Explosive bolts attach the missile stages together through specially constructed, load-carrying interstages with flanges at the ends and, on signal, explode to allow the two stages to separate. A built-in FLSC is used to make a circumferential cut through the interstage skin and structure to allow stage separation. Mechanical, hydraulic, or pneumatic devices can be used to help separate stages. Similarly, mechanisms like ball locks are used for separating the payload from the uppermost missile stage at the very end of powered flight.

An interstage is a cylindrical or truncated cone-shaped structure that connects two missile propulsion stages (Figure 37, left and center). An interstage is, in principle, a simple piece of equipment, but the requisite electrical connections, separation mechanisms, and high strength-to-weight ratios make it rather complex in its adaptation to specific missiles. An interstage structure may also be a framework of trusses with no skin. The purpose of an interstage is to maintain missile integrity during launch and flight, and to ensure stage separation without damage to any missile component or adverse effect on velocity.

Method of Operation: When the propellant in any missile stage is nearly exhausted, the guidance set commands the separation hardware to release the spent lower stage from the interstage connecting it to

the next stage. This electronic signal fires detonators which, in turn, trigger separation mechanisms like explosive bolts or FLSC that sever the structural and electrical connection and let the exhausted missile stage jettison. If atmospheric drag forces are not likely to be strong enough to ensure separation, mechanical, hydraulic, or pneumatic compression springs are placed between the two stages to force them apart. Spent stages may require reverse thrusters or thrust termination to prevent collision of the stages prior to next-stage ignition. When missile stages are joined with a truss interstage, the upper stage will ignite prior to separation from the lower stage. Once the upper stage engines are operating, the interstage will separate. The force of the upper stage engines assists in separating the stages without the need for separation mechanisms.

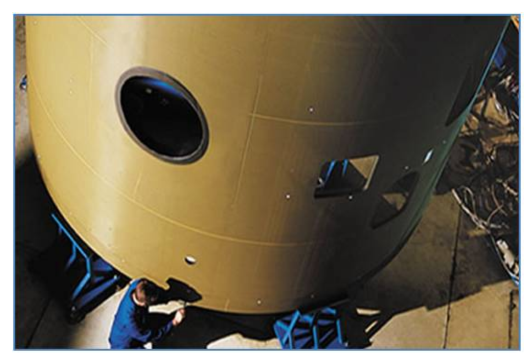






Figure 37: Left: A large composite center-body section designed for a space launch vehicle. (ATK) Center: A typical rocket interstage section. (ATK) Right: A selection of explosive bolts designed for use in space launch vehicles and military applications

Typical Missile-Related Uses: All multi-stage missiles require staging and separation mechanisms. Single-stage missiles with separating warheads also require separation mechanisms.

Interstages are used to carry thrust loads from the lower stage to the upper stages of ballistic missiles during rocket motor burn. Most designs incorporate thin-skin shell coverings to reduce drag by creating a smooth aerodynamic fairing between the stages. They also incorporate the separation mechanisms used to jettison the spent lower stage. Dropping a spent lower stage improves missile range (compared to that of a single stage missile) but must be accomplished cleanly and with proper timing to prevent damage to the missile or deviation from its trajectory.

Other Uses: Prepackaged devices such as explosive bolts have other military applications, most notably in launching weapons or separating external fuel tanks from fighter aircraft. FLSC are routinely used in the oil industry for cutting large pipes. Compression springs are used in the industrial world as shock absorbers and load-levelers.

Appearance (as manufactured): Explosive bolts look like large machine bolts, but with a housing section at the head end. Typically, they measure 7 cm to 10 cm in length and 1 cm to 2.5 cm in diameter, and weigh 50 g to 75 g (Figure 37, right). The housing section contains the ordnance and has wires or cables leading out of it from the internal detonators, which typically require a DC power source. Built-in staging mechanisms almost always use FLSC, a chevron-shaped, soft metal tube of lead or aluminum filled with explosive, typically RDX or HMX. The FLSC is fastened by metal clips to the interior of the interstage

structure holding the two missile stages together and, when initiated by a small detonator, cuts through the structure and skin to release the stages. The tube is a gray metal color, and the explosive is white to whitish-gray in color. The width, height, and weight per unit of length are a function of the thickness of the material it is designed to cut through.

Ball locks do not involve explosives and are sometimes used in payload separation systems. Internally, they use a solenoid/spring/ball-bearing that enables the desired soft disconnect; externally, they appear much like explosive bolts, that is, like a machine bolt with a housing and two wires. Compression springs used for stage separation are long stroke (10 cm to 20 cm), small diameter (2 cm to 4 cm) devices mounted in canisters at several locations (minimum of three) in the rim of the interstage. These steel canisters house steel springs or pistons and have built-in flanges for attachment to the interstage. The hydraulic and pneumatic pistons have built-in fluid reservoirs to pressurize the units when the stages are assembled.

An interstage is a conical or cylindrical structure usually manufactured from graphite composite that has the same outside diameter as the rocket stages it connects (Figure 11). It has connecting frames at each end and locations for separation devices on one end. It has structural supports visible inside the structural walls and end rings or frames used to join it to the missile stages. The length of an interstage is usually equal to about half the outside diameter of the engine nozzle on the next stage above. As described above, an interstage may also be an open-truss framework with no skin.

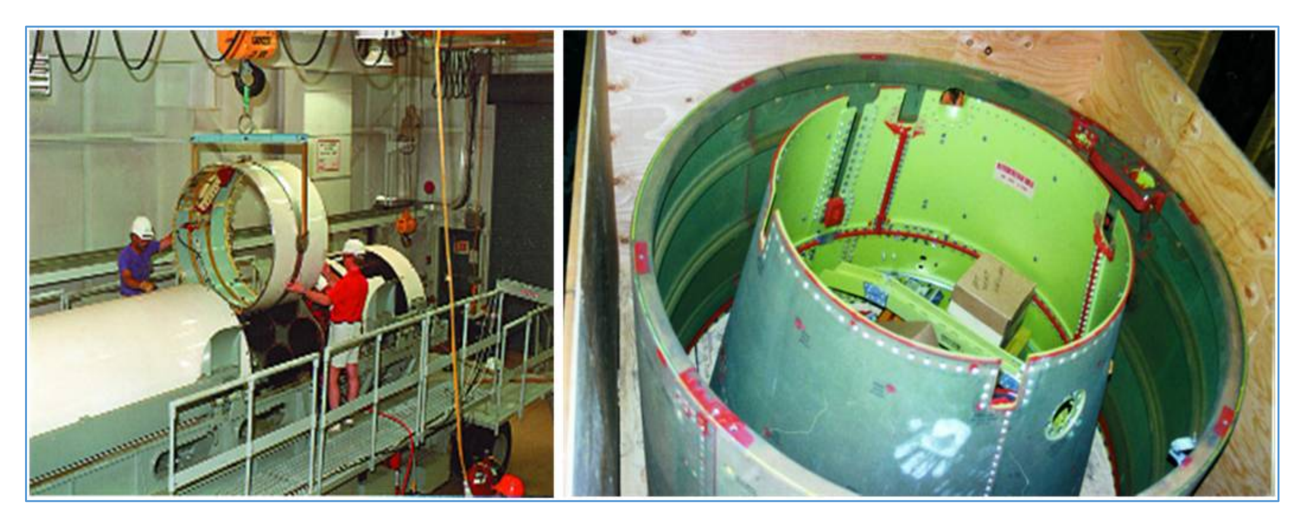


Figure 38 *Left:* An interstage being positioned for attachment. (MTCR Equipment, Software, and Technology Annex Handbook, Third Edition (May 2005)) *Right:* Two interstages in their shipping container. (Ibid)

Appearance (as packaged): Explosive bolts are shipped in simple cardboard boxes with ample internal foam or other packing to mitigate the effects of shocks. Properly shipped boxes are marked with "Danger-Explosive" or "Danger-Ordnance" symbols and are shipped under restrictions governing explosive materials. FLSC are usually shipped in varying lengths in lined and protected wooden boxes. They should be marked with the same "Danger" labels as they are subject to the same shipping restrictions as any ordnance. Ball locks can be packaged and shipped without ordnance restrictions and have no distinguishing features or labels on their packaging. Compression springs are shipped in the uncompressed state in cardboard boxes. Interstages are usually shipped in tailored wooden containers from the manufacturing facility to the missile stage integrator.

3.A.5. Liquid, slurry and gel propellant (including oxidisers) control systems, and specially designed components therefor, usable in the systems specified in 1.A., designed or modified to operate in vibration environments greater than 10 g rms between 20 Hz and 2 kHz.

Notes:

1. The only servo valves, pumps, and gas turbines specified in 3.A.5. are the following:

a. Servo valves designed for flow rates equal to or greater than 24 litres per minute, at an absolute pressure equal to or greater than 7 MPa, that have an actuator response time of less than 100 ms.

b. Pumps, for liquid propellants, with shaft speeds equal to or greater than 8,000 rpm at the maximum operating mode or with discharge pressures equal to or greater than 7 MPa.

c. Gas turbines, for liquid propellant turbopumps, with shaft speeds equal to or great than 8,000 rpm at the maximum operating mode

2. Systems and components specified in 3.A.5. may be exported as part of a satellite.

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- North Korea
- Russian Federation
- United Kingdom
- United States

Global Production



Nature and Purpose: Propellant control systems manage the pressure and volume of liquid, slurry, or gel propellant flowing through the injector plate and into the combustion chamber of a rocket engine. High-pressure tanks or turbopumps force liquid or slurry propellants from fuel and oxidizer tanks into the combustion chamber at high pressure. High-pressure tank systems include the tanks themselves, servo valves, and feed lines to keep propellant flow continuous and void-free during the high acceleration of missile launch. Turbopumps are used to increase the propellant pressure to levels required for high-thrust, high-flow-rate engines. Servo valves can be used to control turbopump speed and thereby control thrust.

Method of Operation: Pressure tank systems use a high-pressure tank, often called a "bottle," which carries a pressurant like nitrogen or helium at up to 70,000 kPa. Pressurant is released to the propellant tanks through a regulator that adjusts the pressure level. The pressurant then pushes the fuel and oxidizer through control valves to the injector at the head of the combustion chamber. Thrust is regulated by opening and closing the control valves the appropriate amount.

Servo valves function to provide nearly exact response with the help of the feedback control system. Their use is almost fundamental to the control of high-power systems such as advanced liquid rocket propulsion systems. They are complicated electromechanical devices that control the flow of propellant through them by balancing forces on both sides of an actuator piston, which regulates the position of the valve pintle. The control signal typically moves a small (hydraulic amplifier) piston that admits variable pressure to one side of the actuator piston. It moves until a new balance is established at a new flow rate. Servo

valves are usually the most costly, sensitive, and failure-prone of all valves because their orifices can easily be clogged by contaminants.

Turbopumps push propellants into the combustion chamber at pressures up to fifty times greater than the pressure at which the propellants normally are stored. Turbopumps are powered by burning some of the rocket propellant in a gas generator; its exhaust gases power a turbine driving the pump. Turbopumps for missiles typically rotate at 8,000 RPM to 75,000 RPM. Engine thrust is regulated by altering the propellant flow to the gas generator (sometimes with a servo valve), and thereby changing the turbine speed of the turbopump and thus the propellant flow into the combustion chamber.

Typical Missile-Related Uses: All liquid propellant rocket engines use either a pressure-fed or a pump-fed propellant delivery system. Pressure-fed systems can be specifically designed for a particular engine or assembled from dual-use components. Turbopumps are usually specifically designed for a particular engine.

Other Uses: Servo valves are common in closed-loop control systems handling liquids. Numerous civil applications include fuel and hydraulic system control in manned aircraft. Other applications involve precision handling of fluids such as in the chemical industry. Turbine drill pumps are popular in the petroleum and deep well industries.

Appearance (as manufactured): Servo valves look much like on-off valves or line cylinders with tube stubs for propellant inlets and outlets in a metal case. Most valves and housings are made of stainless steel. However, these valves are larger than on-off valves because they have a position feedback device. A modern liquid propellant control valve is shown in Figure 39 (left), and a liquid propellant injector plate is shown in Figure 39 (center).



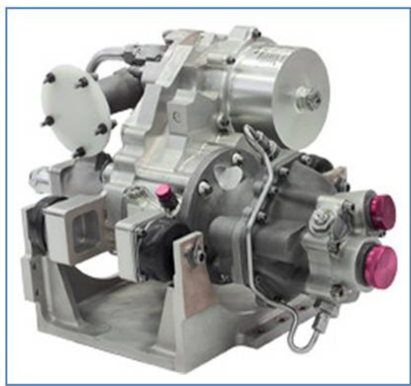


Figure 39: ***Left:*** **A modern liquid propellant control valve. (Allied Signal Aerospace)** ***Center:*** **A liquid propellant injector plate. (Boeing)** ***Right:*** **A turbopump assembly for a space launch vehicle. (Hamilton Sundstrand)**

Turbopumps are usually housed in metal cases and are sized for specific applications. Although they resemble automotive or truck turbochargers, they are much larger and can weigh several hundred kilograms. Turbopumps for liquid propellant rocket engines may have a separate pump and turbine assembly for each propellant (e.g., for the fuel and for the oxidizer), or a single unit that combines both pumps and the turbine drive mechanism. A turbopump assembly for a space launch vehicle is shown in

Figure 39 (right). The ribbing of the housings is typical of turbopumps because they provide good strength and light weight; however, some turbopumps have smooth metallic housings.

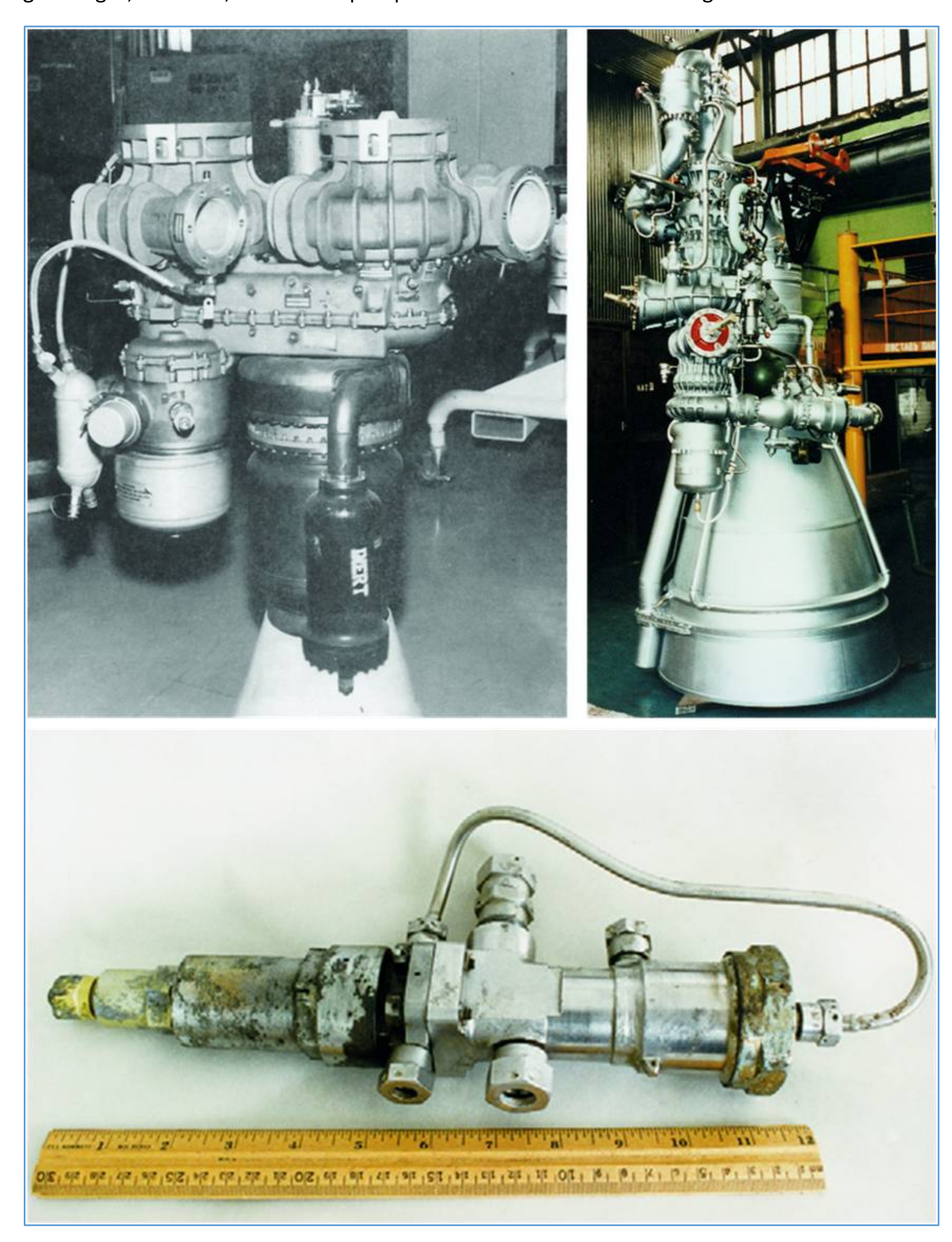


Figure 40: ***Top left:*** **A multi-shaft turbopump assembly. (Aerojet)** ***Top right:*** **A single-shaft turbopump. (Aerojet)** ***Bottom:*** **A servo valve from a Scud missile. (MTCR Equipment, Software, and Technology Annex Handbook, Third Edition (May 2005))**

Appearance (as packaged): Servo valves are packaged like other valves, especially on-off valves. Inlets and outlets are plugged to prevent contamination. The valves are placed in vacuum-sealed plastic bags or sealed plastic bags filled with nitrogen or argon to keep the valves clean and dry. They may sometimes be double bagged and are usually shipped inside a container, often an aluminum case with a contoured foam liner. Small turbopumps are often packaged and shipped in aluminum shipping containers. Depending on size and interface features, a large turbopump may be packaged and shipped in a custom-built shipping crate, with pump supports built in. Turbopumps may also be shipped as a breakdown kit in which separate components are packaged for assembly after receipt.

3.A.6. Specially designed components for hybrid rocket motors specified 2.A.1.c.1 or 20.A.1.b.1.

Nature and Purpose: Hybrid rocket motors use both solid and liquid propellants, usually a solid fuel and a liquid oxidizer. Because flow of the liquid oxidizer can be controlled, hybrid motors can be throttled or shut down completely and then restarted. Hybrid rocket motors thereby combine some of the simplicity of solid rocket motors with the controllability of liquid rocket engines.



Figure 41: A hybrid sounding rocket motor. (NASA)

Method of Operation: Hybrid rocket motors use either pressurized tanks or pumps to feed oxidizer into the combustion chamber, which is lined with solid fuel. The pumps are driven by a gas generator powered by its own fuel grain or some other source of fuel. The liquid oxidizer burns the solid fuel inside the hollow chamber, and the hot, expanding gases are expelled through the nozzle at supersonic speed to provide thrust. As in a solid propellant rocket motor, the outer casing of the combustion chamber is protected from much of the heat of combustion by the fuel itself because it burns from the inside outward.

- Japan
- Russian Federation
- Republic of Korea
- United States

Global Production



Typical Missile-Related Uses: Hybrid rocket motors may be used to power space launch vehicles, sounding rockets and ballistic missiles.

Other Uses: N/A

Appearance (as manufactured): A hybrid rocket motor has an oxidizer injector mounted in the top of the high-pressure motor case and a converging/diverging nozzle at the bottom. The injector has valves and piping either from a pressure tank or from a tank and an associated pump. The combustion chamber is usually fabricated either from steel or titanium,

which may be black or gray, or from filament-wound graphite or glass epoxy, which is usually yellow or brown. The chamber is lined with thick, solid propellant having one of a variety of configurations and looking like a single cylinder with a hollow center, concentric cylinders, or wagon wheels. Nozzles are made of ablative material, which is often brownish, or high-temperature metals, and they may have high-temperature inserts in their throats (Figure 41).

Appearance (as packaged): Hybrid rocket motors may be shipped fully assembled or partially assembled, with tanks and associated hardware packaged separately from the combustion chamber and attached nozzles. Fully assembled units are packaged in wooden crates; components are packaged in wooden crates or heavy cartons. Legally marked crates are labeled with explosives or fire hazard warnings because the missiles are fueled with solid propellant. However, because motors contain only fuel and no oxidizer, they are less hazardous than normal solid propellant rocket motors.

3.A.7. Radial ball bearings having all tolerances specified in accordance with ISO 492 Tolerance Class 2 (or ANSI/ABMA Std 20 Tolerance Class ABEC-9 or other national equivalents), or better and having all the following characteristics:
a. An inner ring bore diameter between 12 and 50 mm;
b. An outer ring outside diameter between 25 and 100 mm; and
c. A width between 10 and 20 mm.

Nature and Purpose: Radial ball bearings produced to high specifications have important aerospace applications, most significantly in the turbopumps of rockets used in rockets and also in all types of gas turbine engines powering air vehicles.

Method of Operation: Radial ball bearings (sometimes referred to as deep-groove or angular contact bearings), are commonplace in all types of machinery. Rolling element bearings of this type enable the moving parts of machinery to run smoothly with minimal friction. The races are the circular metal housings, forming an inner ring and outer ring, and containing the balls. One of the races is usually held in a fixed position within in a machine while the other supports a rotating shaft. The balls contained between the races are free to rotate, together with the race supporting the moving shaft. Radial ball bearings support radial, thrust, moment, reversible thrust or combination loads.



Figure 42: Radial ball bearings manufactured to the ISO 492 tolerance class required by 3.A.7. (GMN)

Typical Missile-Related Uses: Radial ball bearings have a range of applications in missile-related systems, including in the following: turbopumps of liquid rocket engines, all main shafts and auxiliary drives of turbojet, turbofan and turboprop engines, and turboprop reduction gearboxes.

- Argentina
- Brazil
- Canada
- China
- France
- Germany
- India
- Indonesia
- Italy
- Japan
- Malaysia
- Mexico
- Poland
- Romania
- Russian Federation
- Singapore
- Sweden
- Thailand
- United Kingdom
- United States

Global Production



Other Uses: High specification radial ball bearings have a vast range of applications in machinery for industrial, transportation, agricultural, manufacturing, medical and other purposes.

Appearance (as manufactured): Metallic double ring construction, silver in color, with a smooth finish, sometimes polished. The balls are generally visible between the housing races, and the races will rotate freely (Figure 42).

Appearance (as packaged): Radial ball bearings are typically packaged in small cardboard boxes with the manufacturer's branding.

3.A.8. Liquid or gel propellant tanks specially designed for the propellants controlled in Item 4.C. or other liquid or gel propellants used in the systems specified in 1.A.1.

- China
- India
- France
- Germany
- Japan
- United States
- Russian Federation

Global Production



Nature and Purpose: Liquid rocket engines consume oxidizer and fuel quite rapidly, so it is necessary to pressurize the liquid tanks that carry propellants in flight, in order to feed high liquid flows to engines. The vast majority of the mass of a rocket stage is propellant, because rocket performance (range and payload) depends on achieving a high ratio of propellant mass to non-propellant mass. Therefore, a liquid propellant tank is specialized to be very lightweight relative to the contained volume. In order to withstand internal pressures with high structural efficiency, rocket tank shapes are cylinders with domed ends, sometimes spheres or occasionally conical, and variations of these shapes.

On a liquid rocket stage for either ballistic missiles or space launch vehicles, separate tanks are used to carry the oxidizer and fuel, which must not come into contact before they reach the engine combustion chamber(s). The largest rocket stages use liquid oxygen to burn either kerosene or liquid hydrogen fuel. Such stages with these propellants are typically used for space launch vehicles, and potentially for ballistic missiles. However, oxygen and hydrogen are very cold as liquids, so boiloff losses occur even with insulation, and

frost accumulates on the outside of tanks. Ballistic missiles are more likely to use propellants that are controlled by Item 4.C. in the MTCR Annex, which can be loaded well in advance and stored inside the missile for ongoing launch readiness. Examples include nitric acid and nitrogen tetroxide, and kerosene or hydrazine fuels.

Figure 43 shows two very different propellant tank examples, both controlled by Item 3.A.8. On the left is an individual propellant tank roughly one meter in size, appropriate for an upper stage or a spacecraft. The right side of Figure 43 is a diagram of an integrated tank pair for a space launch vehicle. The 8.4-meter diameter oxidizer and fuel tanks are joined together by an intertank structure (note the corrugations for stiffness in the absence of internal pressure). While the front end of this particular oxidizer tank is shaped for aerodynamic flight, missile tanks typically would have another stage or a payload above the forward (upper) tank.



Figure 43 ***Left:*** **A typical liquid propellant tank developed for a range of space applications. (EADS)** ***Right:*** **A diagram of the external tank used by a space vehicle launch engine, showing the separated oxidizer and fuel tanks. (NASA)**

While solid-propellant rockets are more easily stored and transported in any orientation, essentially always ready to launch, liquid propellant tanks and the rocket systems of which they are a core component offer some advantages over solid propellant systems. Liquid propellants produce higher rocket exhaust speeds, which either reduces the mass of the vehicle or increases the range and payload potential. Liquid fuels can also be throttled, shut down, and re-ignited as a mission's objectives require, providing far greater ability to manipulate and control overall performance of the rocket system. The sub-components required to achieve this level of control also makes liquid propellant tanks and engines extremely complex.

Method of Operation: In order to be lightweight, large tanks for main rocket stages tend to operate at very low pressures, below 0.35 MPa (50 psi). This pressure level is sufficient to feed the kind of rocket engines that use pumps to increase the pressure, typically above 7 MPa (1,000 psi) so that combustion chambers and nozzles can be relatively compact. In contrast, small tanks for upper stages and spacecraft are typically rated for 2 to 4 MPa (300 to 600 psi) in order to directly feed rocket combustion chambers

without pumps. This latter "pressure-fed" mode of operation compromises on medium pressures for tanks and engines as well. One special case is gel propellants that have high viscosity, so high pressures are needed to push the materials out of the tank. While liquid propellant tanks must withstand internal pressure, they are generally not referred to in rocket engineering as "pressure vessels," a term usually reserved for containers that store gases at much higher pressures.

As liquid propellants are expelled from tanks in flight, pressure is maintained by filling the expanding ullage volume with non-reacting gases referred to as "pressurants." For example, liquid oxygen might be displaced by oxygen vapor, or by helium which has less mass. A significant operational consideration is that liquid propellant must reach the outlet plumbing under conditions of varying acceleration and gravity effects. Liquid settles toward the bottom of main stage tanks in flight, but the tanks may need internal panels to reduce liquid sloshing. For upper stages or maneuvering reentry venicles, tanks may need to deliver liquid under wider ranging conditions of acceleration, including free-fall (microgravity). Such tanks use "propellant management devices" (PMDs) so that the liquid, not the pressurant gas, reaches the engines through the tank liquid outlet port. PMDs include surface tension devices and flexible bladders or diaphragms to positively separate the liquid and gas phases.

Paired liquid oxidizers and fuels are known as bipropellants. Some smaller rocket systems use a single tank of propellant, or monopropellant, such as hydrazine. Instead of combustion, monopropellants release chemical energy upon decomposing, usually initiated by a catalyst in the engine. Hydrazine decomposes into hydrogen, nitrogen, and ammonia gases, for which the catalyst is granular alumina ceramic with an iridium metal coating. Another example is hydrogen peroxide, which decomposes into oxygen and water (as steam). Monopropellants offer propulsion system simplicity, but they are less efficient than bipropellants.

Typical Missile-Related Uses: Specially designed tanks are the major structural component of every liquid propellant rocket. Most of the mass of each missile stage is propellant, so most of the rocket length is the tanks, usually two per stage joined by an intertank structure. By comparison, liquid rocket engines typically occupy a small fraction of stage length, for first and second stages at least. Ballistic missile upper stages are smaller overall, so their tanks are relatively shorter relative to the missile diameter, potentially spherical. The largest space launch vehicles use liquid propellants for their main stages, so large specialized liquid propellant tanks are essential. Liquid propellant tanks can be used by maneuvering re-entry vehicles, in which case small tanks might be internal, configured differently from a main stage.

Other Uses: Small liquid propellant tanks are used in many satellites, science spacecraft, and space exploration vehicles.

Appearance (as manufactured): Propellant tanks for the large main stages of rockets are long cylinders, typically one to several meters in diameter, with metal walls just a few or several millimeters thick. Their length might be anywhere from one or two to roughly ten times the diameter, depending on their use for a lower stage (long) or an upper stage (short). Such large tanks are often made of aluminum alloys, and sometimes steel. Flight tank walls are sufficiently thin that tapping on them with hands or knuckles tends to produce a hollow sound or a low-pitched ringing. Often the thin metal is bare but it could be painted. An insulation layer on thin metal would change the acoustic effect.

Propellant tanks for rocket upper stages, maneuvering vehicles, and satellites can range from 0.1 meter to over 1 meter in diameter. Typically tanks of this size operate at higher pressures than the tanks of large rocket stages. Small tanks are often made of titanium alloys, because the higher pressures dictate high performance materials and the small size makes titanium relatively affordable. In addition, small tanks tend to have lengths not much more than their diameter, including spherical shapes that maximize volume per mass.

Some tanks used for rocket propulsion have composite construction, typically with carbon fiber in epoxy resin. Their appearance is shiny black or dark gray. Most tanks having such an appearance are not liquid propellant tanks, but rather they are pressure vessels for gases such as helium or nitrogen. Some specialized applications do use composite construction for liquid propellant tanks. Composite pressure vessels for gases are usually rated for pressures well above 10 MPa (1450 psi) and their walls are relatively thick, wrapped with many layers of carbon fiber. Composite tanks for liquids are usually rated for pressures well below 10 MPa. Liquid tanks are lightweight (see numbers below), while pressure vessels for gas are much heavier.

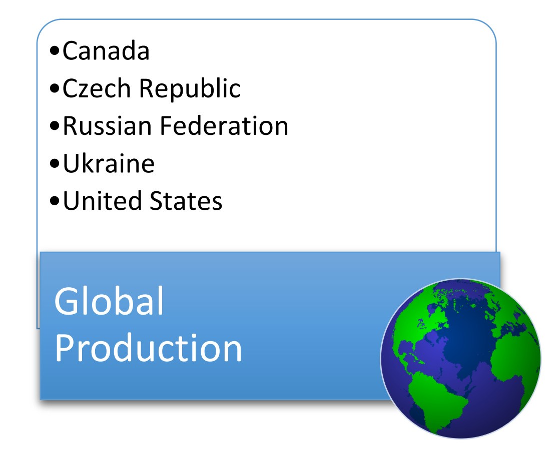
Appearance (as packaged): Flight tanks are effectively fragile, so typically they need to be treated very carefully during and after manufacture. Propellant tanks are expensive critical components of all rockets and as such are shipped in specially designed containers often with shock mounts and internal struts that prevent movement en route. Large tanks are transported on special vehicles, e.g. customized semitrailers with little or no additional packaging. Flight tanks for liquid propellants are very lightweight relative to their volume (5 to 50 kg per cubic meter), so typically shipping weight is dominated by the containers and/or fixtures.

3.A.9. 'Turboprop engine systems' specially designed for the systems in 1.A.2. or 19.A.2., and specially designed components therefor, having a maximum power greater than 10 kW (achieved uninstalled at sea level static conditions using the ICAO standard atmosphere), excluding civil certified engines.

Technical Note:
For the purposes of Item 3.A.9., a 'turboprop engine system' incorporates all of the following:
a. Turboshaft engine; and
b. Power transmission system to transfer the power to a propeller.

Nature and Purpose: Turboprop engine systems are air-breathing gas turbine power plants running on aviation turbine fuel (AVTUR) and driving an airscrew propeller by a reduction gearbox.

Method of Operation: Turboprop engines work on the same principle as the turbojet, taking in air from an inlet, and raising its pressure with a compressor, mixing the compressed air with fuel in a combustion chamber and burning it. The expanding gases travel through a turbine which drives the compressor. As the turbine and compressor are connected by a shaft which runs through the center of the engine, the process is continuous.



In a turboprop, the turbine is also connected to the propeller by a gearbox. Compared to a turbojet engine, which depends on the high kinetic energy of gases expelled in a jet through the nozzle at the rear, the turboprop's turbine captures more of the expansion energy generated by combustion to drive the propeller. In order to do this the turbine designed for a turboprop engine has extra stages compared to a turbojet, and the turboprop produces only low residual jet thrust. A turboprop engine may be of two-shaft design, and in this case the propeller is driven by the low pressure turbine. In simple terms, a turboprop moves a large mass of cool air slowly outside the engine through a relatively slow-moving propeller, compared to a turbojet where a smaller charge of hot gas passes quickly and noisily through the engine. The turboprop is best suited to air vehicles travelling at speeds up to 400 mph (645 km/h, 378 knots). Up to this speed, the turboprop is notably fuel efficient, and is well suited for long range or high endurance flight. It has clear performance advantages over reciprocating gasoline engines when operating in this regime and is likely to be more reliable and have a longer service life than a piston engine.

All turboprop engines require a high-ratio speed-reduction gearbox to step down the turbine speed to a workable speed for the propeller, and this gearbox is integrated with the engine. The propeller is a separate unit, generally an advanced design of constant speed variable pitch type, which relies on a self-contained mechanism to change the pitch of the blades as power is applied and also to control propeller rotational speed. The complete turboprop engine system with its propeller and gearbox is consequently more expensive to manufacture than a turbojet, and is regarded as far less suitable for expendable applications.

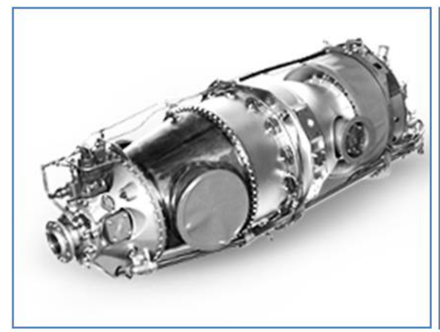
The use of turboprops to propel air vehicles at airspeeds closer to the speed of sound presents problems because the propellers lose efficiency at high speeds due to an effect known as wave drag. Higher engine power requires a greater number of propeller blades or increasing the diameter of the propeller, but propeller tip speeds must be kept in the subsonic range. Weight and complication grow if co-axial contra-rotating propellers (CRP) are used. The turbojet and turbofan are more suited to propulsion closer to the speed of sound. In theory, a turboprop engine design known as an open rotor or propfan, which uses highly swept propeller blades, offers the prospect of higher speeds closer to that achieved with jets, but this engine technology is still under development.

Typical Missile-Related Uses: Turboprop engines can be used to power unmanned aerial vehicles, especially those required to operate over long ranges or on missions of long endurance. Turboprops do not have the characteristics to power ballistic missiles or high-speed cruise missiles, but can provide an air vehicle with a combination of qualities including reasonable speed, relative quietness, and good load-carrying characteristics, combined with fuel efficiency for long range or long duration flight. The potential

clearly exists for development of a flying bomb type of turboprop UAV operating at moderate speeds over extremely long ranges.

Other Uses: Turboprop engines power a wide variety of light and medium military and civilian aircraft and some hovercraft. Gas turbine engines closely related to aircraft turboprops are widely used in pumps and generator sets.

Appearance (as manufactured): Turboprop engines (Figure 44) are cylindrical units characterized by an outer casing which may vary in diameter along its length. Turboprop engines seldom conform to the classic layout of a jet engine, where the compressor fan is visible at the front and the open jetpipe is seen at the rear. Instead the turboprop generally resembles a tube closed at both ends. An intake is generally visible, although not always at the front of the engine. The casing may carry fuel pipes, thermocouples and various accessory boxes. With its propeller detached, a turboprop engine is harder to identify. The propeller mounting hub is a small diameter disc at the end of the engine with several drilled holes around the circumference and mounting pegs.





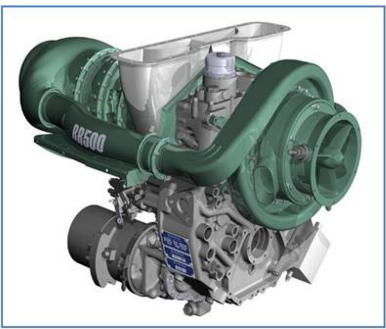


Figure 44: *Left:* A turboprop engine used to power UAVs controlled under 19.A.2 of the MTCR. (Pratt & Whitney Canada) *Center:* A turboprop engine used to power a UAV, controlled by 1.A.2 of the MTCR. (Honeywell) *Right:* A turboshaft engine designed for use in a range of UAV applications. (Rolls Royce, plc)

Gas turbine engines are extremely compact and have a high power-to-weight ratio. A turboprop engine capable of producing 900 kW can measure slightly less than 2 m in length and 0.5 m in diameter and may be mistaken for a heater or industrial pump when seen outside an aerospace context. Large turboprop engines may be as long as 3.5 m and weigh more than 1 ton. With its propeller attached, a turboprop engine is hard to mistake for anything else.

Appearance (as packaged): A turboprop engine should normally be mounted horizontally on a transit stand or servicing stand which comprises a base (sometimes wheeled) and a cradle supporting the engine at a convenient height for handling, and with provision for lifting by a fork truck. The stand may be fitted with shock attenuating devices for transport. The air intake(s) are covered with blanking plates for protection and the complete engine may be entirely covered by a purpose-made plastic jacket closed by fasteners and buckles. A separate covering is sometimes applied to the propeller when fitted. The engine and propeller may otherwise be covered with plastic sheet. Turboprop engines may be carried in wooden crates or in purpose-built fiberglass or metal containers.

When separated from the engine, propellers are usually carried or stored vertically on a triangular stand, supported at the hub. Under most circumstances, a packaged turboprop engine is likely to be closely accompanied by documents providing its history and maintenance state.

3.A.10. Combustion chambers and nozzles for liquid propellant rocket engines or gel propellant rocket motors usable in subsystems specified in 2.A.1.c.2. or 20.A.1.b.2.

Nature and Purpose: For liquid and gel propellants, rocket engine combustion chambers have the function of containing the mixing, reacting propellants and their combustion products at high pressures. The reacting substances must remain in the chamber for a sufficient duration that essentially complete combustion can occur before the resulting high-temperature gases reach the nozzle throat on their way to exiting the engine.

A rocket nozzle consists of a converging section at the downstream end of the combustion chamber, followed by the narrow throat. After the throat is a diverging section, generally a bell-shaped or conical shell structure which controls the expansion of the gases. The flowing gases are squeezed by the converging section, then they escape through the throat at the speed of sound. In the diverging section, the gases quickly accelerate to multiple times the speed of sound.

The combustion chamber and nozzle are often fabricated as one-piece items or at least they usually become permanently joined together, effectively inseparable. Hence the term “thrust chamber” is often used to refer to the resulting component that includes both. At the end opposite to the throat and nozzle, a combustion chamber is joined to its injector, a complicated component having fluid passageways for the individual propellants (see MTCR Annex Item 3.A.5.). Before mixing and burning, oxidizer and fuel enter the combustion chamber separately through the injector, which typically also functions as the upstream wall of the combustion chamber.

Method of Operation: The shape of a rocket nozzle is fundamental to its operation. In the absence of the bell-shaped or conical diverging section, the escaping gases would expand in all directions instead of going in the one desired direction. If the conical section was instead a long tube, the same uncontrolled expansion would occur at the end of the tube. Instead, the optimal nozzle shape lets the gases expand gradually while keeping the vast majority of the flow lined up along the axis, in order to efficiently produce thrust by conservation of momentum.

A key operational aspect of combustion chambers and nozzles is the need to withstand high temperatures and high mechanical stresses simultaneously. Considering that material strengths are reduced at high temperatures, thrust chamber walls (including nozzles) are generally designed to operate at lower temperatures than the reacting gases. A large rocket thrust chamber typically has cooling passageways built into the wall, through which liquid fuel flows to keep the nozzle much cooler than the flame itself.

Fuel is injected into the wall using a manifold where the nozzle has a large diameter. The term

"regenerative cooling" applies because the heat energy reaching the nozzle wall is not wasted. This energy warms the fuel and is carried back into the combustion chamber, improving rocket performance compared to throwing the heat away. For some engine designs, the fuel vaporizes while flowing within the wall, then the vapor may be used to power a turbine before being injected into the combustion chamber.

It is more challenging to implement flow passageways in smaller, thinner walls, so small thrust chambers have used other methods for cooling during operation. One method is to configure injector flows to provide a thin layer of uncombusted fuel flowing along the wall, inside the chamber. Compared to large engines, it is relatively affordable for small engines to be made of expensive refractory metals, and more exotic high-temperature materials have sometimes been used. Radiation cooling refers to simply letting the wall glow red-hot or even white-hot, which emits heat as infrared energy and some visible light. Thrust chambers lacking cooling channels typically operate at much lower combustion pressures than main engines, which helps to reduce wall heating.

The operation of combustion chambers and nozzles is essentially the same for liquid propellants and gel propellants. Gels are effectively high-viscosity liquids, so the primary operational difference is that higher pressures are needed to push gels through small passageways. Therefore, gel propellants may be less practical when cooling passages are used.

Typical Missile-Related Uses: Large combustion chambers and nozzles are major pieces of the main engines of liquid propelled ballistic missile stages. Large rocket thrust chambers are similarly found on the main engines of liquid propelled space launch vehicles. Their smaller counterparts can be used by upper stages and maneuvering re-entry vehicles. Small liquid rockets are also used for attitude control to steer the main stages of ballistic missiles, including some missiles that use solid propellant for primary thrust. Liquid rockets are versatile for these control functions because valves can be used to vary the thrust or to turn engines on and off.

Other Uses: Satellites and spacecraft use a wide variety of small liquid rocket engines for maneuvering and attitude control, including orbit maintenance and interplanetary transfers.



Figure 45: ***Top left*****: A liquid rocket engine with a large, regeneratively cooled nozzle. (MTCR Equipment, Software and Technology Handbook, Third edition (May 2005))** ***Bottom right*****: Side view of a regeneratively cooled liquid rocket nozzle, joined to its combustion**

Appearance (as manufactured): Figure 45 shows a large thrust chamber by itself, and also a complete liquid rocket engine that incorporates such a thrust chamber. For both, the overall size is dominated by the diverging section of the nozzle, typical but not necessarily so. In both images, it can be seen that the wall is made of many small tubes (for cooling flow) that run from the nozzle exit toward the throat, supported by structural rings around the outside. Alternatively, missile thrust chambers may have internal cooling channels between layers, in which case the visible surfaces appear smoother. Regardless of the chamber wall construction, flow passageways (ducts, tubes, or pipes) feeding propellant into the wall are likely to be apparent. For the main stages of ballistic missiles and space launch vehicles, liquid rocket thrust chambers have historically ranged in size from roughly one to six meters long, and 0.3 m to 4 m in diameter at the large end of the nozzle. The corresponding thrust over this wide range of sizes is approximately 5 tons to over 500 tons.

For small thrust chambers that lack cooling channels in the wall, one common type of liquid rocket engine produces roughly 500 Newtons of thrust (0.05 ton, or 110 pounds). Many satellites have one of these "apogee engines," while few engines larger than this have been used as part of a satellite. The thrust chamber length for such engines can vary from 0.25 m to 0.7 m, with a nozzle exit diameter from 0.15 m to 0.4 m. Satellites also use multiple smaller thrust chambers for fine maneuvering and attitude control (rotational maneuvering). Smaller liquid rocket engines are more commonly known as thrusters, and the smallest ones use a single propellant that decomposes instead of mixing oxidizer and fuel. Figure 46 shows a small monopropellant thruster that uses radiation cooling to keep the metal wall at a somewhat lower temperature than the gases.



Figure 46: A small rocket thruster that uses liquid hydrazine monopropellant. The thrust chamber wall is thin metal without cooling passageways, so the surfaces are darkened in color due to high temperatures. The bright metal portion remains cooler due to liquid flow through the injector. Overall length is approximately 0.1 m. (Aerojet Redmond and Lawrence Livermore National Laboratory)

Liquid rocket nozzles and combustion chambers are typically made of metals that might be shiny, a shade of gray, or otherwise darkened. In the absence of liquid cooling passageways, metal alloys used for combustion chambers and nozzles range from stainless steel to alloys of nickel and columbium (niobium), or other refractory metals for higher temperatures. Cooling passageways make it practical to use materials capable of only lower temperatures, such as copper and possibly aluminum alloys. The inside of a thrust chamber may look different from the outside, due to the presence of coatings or different layers. While the largest rocket thrust chambers are usually made of metal, small ones might include ceramic materials.

Appearance (as packaged): All missile parts need to be made as lightweight as practical, so they are relatively fragile. Large liquid rocket thrust chambers and nozzles, if shipped separately, are likely to be seen in wooden crates or surrounded by specially configured structural frames to protect them from damage. Typically there would be plastic sheeting to keep them clean. Small rocket thrust chambers can be shipped in crates or in special rigid boxes made of metal or plastic. Regardless of the outer solid material, internal soft foam would be configured for the shape of the object.

3.B. Test and Production Equipment

3.B.1. "Production facilities" specially designed for equipment or materials specified in 3.A.1., 3.A.2., 3.A.3., 3.A.4., 3.A.5., 3.A.6., 3.A.8., 3.A.9., 3.A.10. or 3.C.

Nature and Purpose: Subsystem production facilities are often industrial areas designed to manufacture the major assemblies listed in Items 3.A.1., 3.A.2., 3.A.3., 3.A.4., 3.A.5., 3.A.6., 3.A.8., 3.A.9., 3.A.10. and materials in Item 3.C. There may be equipment to test these devices at the component level and as assemblies prior to transferring the subsystem to storage or to the main assembly facility. Turbojet, turbofan and turboprop engines designed to power UAVs may be manufactured at civil or military aircraft production facilities. Danger and explosive safety placards are usually present in these facilities.

Method of Operation: Jigs and fixtures are used to support, align and assemble individual components such as turbojet, turbofan and turboprop engines, fuel and oxidizer tanks, motor cases and engine assemblies. Molds, dies and mandrels are uniquely designed and used in the production of component parts. Overhead cranes are used to move the raw material and components from their shipping containers and dollies onto the assembly jigs. Pyrotechnic devices are installed on interstage sections in remotely located facilities. Proper materials and manufacturing procedures are critical to the production of reliable liquid propellant pumps and servo valves.

Typical Missile-Related Uses: Production facilities are used to manufacture or produce UAV and rocket subsystems from raw materials or assemble them from components imported from external sources. The finished subsystems are loaded into individual containers or crates and shipped to a facility for long-term storage or to facilities for final assembly and use.

Other Uses: Production facilities used to manufacture MTCR-controlled UAV engines, build rocket motors and engines, and test equipment, can also be used to manufacture products associated with civil and military aircraft.

Appearance (as manufactured): These facilities may use overhead cranes to move UAV and rocket subsystems from one jig or area to another. Assembly jigs and fixtures used in the production of rocket systems are usually large and heavy structures. Their overall length and width are roughly 20% to 30% larger than the system that they are designed to assemble. They weigh hundreds or even thousands of pounds. Interstage manufacturing facilities contain explosive hazards and include suitable grounding and other hazard-mitigating procedures. Interstage manufacturing facilities are associated with explosive storage areas and may be located in remote regions far from populated areas. Liquid propellant pumps and servo valves require specialized materials and precision machining equipment to produce reliable products.

Liquid propellant rocket engine production facilities are currently smaller than they were several decades ago, when large numbers of missiles and systems were being manufactured. Medium-range ballistic

missiles and smaller missiles could be fabricated in a facility that would look much like any large, well-equipped machine shop. In addition, there would need to be a quality-assurance facility with laboratories, including clean rooms and air-flow benches, granite level benches and so forth, with precision measuring devices, including scanning electron microscopes (SEMs), gas sniffers with a location capability of less than 5 parts per million and other specialized measurement devices as required.

Appearance (as packaged): New equipment or replacement spare parts for these types of facilities are sometimes large and too heavy to be packaged and shipped to the production plant as complete units. Instead, component parts are shipped separately in crates or on protected pallets for onsite assembly. They will be securely fastened to the crate to restrain motion and prevent damage. Smaller jigs may be individually crated or palletized for shipment.

3.B.2. "Production equipment" specially designed for equipment or materials specified in 3.A.1., 3.A.2., 3.A.3., 3.A.4., 3.A.5., 3.A.6., 3.A.8., 3.A.9., 3.A.10. or 3.C.

Nature and Purpose: Each subsystem production facility designed to produce the items listed in 3.A.1., 3.A.2., 3.A.3., 3.A.4., 3.A.5., 3.A.6., 3.A.8., 3.A.9., 3.A.10. and 3.C. contains the specialized jigs and fixtures necessary to form, machine, assemble and test the propulsion system and equipment sub-assemblies specified in 3.A.1., 3.A.2., 3.A.3., 3.A.4., 3.A.5., 3.A.6., 3.A.8., 3.A.9., 3.A.10. and 3.C. Industrial machining equipment is used to manufacture turbojet, turbofan and turboprop engine components. Additive manufacturing machines are emerging as a viable option for producing injectors and associated components. Large X-ray equipment may be available to check for voids and cracks in the solid propellant rocket motor (see MTCR Annex Item 15.B.5.). Electrical and electronic test equipment is used to support actuator and other subcomponent level functional and operational testing.

Method of Operation:

Turbojet and Turbofan engines: Turbojet, turbofan and turboprop engines used to power UAVs (including cruise missiles) are manufactured using essentially the same technology as their larger counterparts in the civil and military aviation industry. These engines are machined from temperature-tolerant materials using standard aviation tooling and assembly procedures.

Solid Propellant Rocket Motors: Equipment used to build solid propellant rocket motors includes metal-working machinery, possibly continuous filament-case-winding equipment.

Rocket motor cases are manufactured from high-strength steel into the designed case size and strength, or they are wound from composite fibers to produce lightweight motors as strong as steel cases.

Insulating Material / Liner: The solid propellant rocket motor requires insulating material between the case wall and the propellant to prevent the case wall from failing due to excessive heat from combustion. This insulation is often a thin layer of rubber or a layer of propellant without the oxidizer component added (also known as “inhibited propellant”).

Nozzles: Nozzles for solid propellant rocket motors are manufactured from graphite composite material and require specialized equipment to construct. They are built from ingots composed of carbon fiber wound structures that are heat-treated to cure resin and fibers into the desired shape. These ingots are further densified by adding impregnating resins and curing to still higher temperatures, often at elevated pressures within an inert atmosphere. The process may be repeated a number of times to increase the density of the final article to meet design criteria. Isostatic presses may be used during this process. Once the ingots are produced, they are machined to the designed nozzle shape using industrial machine shop facilities that incorporate dust collection equipment.

Liquid Propellant Rocket Engines: CAD/CAM (computer-aided design and computer-aided manufacturing) software is used extensively in today's rocket factories and supporting facilities that provide component parts to the engine-system integrator. Propellant on-off valves, for example, require milling machines to manufacture metal parts such as cases, including valve seats, and pintle valves. Electromagnetic coils are attached to the pintles, and the valves are positioned in assembly jigs (fixtures) for welding by specialized equipment. Assembled valves go through an array of inspections to ensure that they meet the specification requirements, inspections for which specialized equipment is required. Leak checks require the use of high-pressure helium and a gas chromatograph with a detection capability to at least five parts per million. Numerous other acceptance tests are completed during production and delivery.

Electrical Discharge Machining (EDM) has been used extensively in the manufacture of injectors. When first developed, it was controlled by set-up fixtures and manual controls. Currently, computer-controlled EDM and CAD/CAM links are the norm. Additive manufacturing machines are emerging as an option for making injectors.

Every component in the liquid propulsion system has an analogous set of production equipment to fabricate components and verify that they meet specified requirements. After components are tested and delivered to the final assembly area, the propulsion system is assembled and numerous measurements and checks are made to confirm the device as built corresponds to design specifications.

At that point, the system could be installed in a test facility to verify by operation that the system meets system requirements. Interstage separation devices are manufactured in remote areas that incorporate explosive safety precautions. Safe and arm devices are tested to insure the pyrotechnic devices are safe to handle but will activate on command. Bridge wire testing confirms the electrical leads are connected to the explosive detonators and that the circuit through the safe and arm device is complete.

Typical Missile-Related Uses: The components and assemblies manufactured at these facilities are used to build or test turbojet, turbofan, turboprop, ramjet, scramjet, pulsejet, and combined-cycle engines, rocket motor cases, rocket staging mechanisms, liquid propellant control systems and tanks and the lining and insulation used in solid propellant motors. Each of these items is required to manufacture or assemble a MTCR-controlled UAV or rocket system.

Other Uses: Production equipment used to manufacture MTCR-controlled UAV engines, solid propellant rocket motors, liquid propellant rocket engines and associated test equipment can also be used to manufacture products associated with civil and military aircraft and satellite or spacecraft subassemblies.

Appearance (as manufactured): Equipment and fixtures used in the production of solid propellant rocket motors are usually large and heavy structures.

Appearance (as packaged): UAV and rocket assembly jigs and fixtures are often too large and heavy to be packaged and shipped to the production plant as complete units. Instead, component parts are shipped separately in large crates or protected on pallets for assembly onsite. They will be securely fastened to the crate to restrain motion and prevent damage. Smaller jigs may be individually crated or palletized for shipment.

3.B.3. Flow-forming machines, and specially designed components therefor, which:

a. According to the manufacturers technical specification can be equipped with numerical control units or a computer control, even when not equipped with such units at delivery; <u>and</u>

b. Have more than two axes which can be co-ordinated simultaneously for contouring control.

Note:
This item does not include machines that are not usable in the "production" of propulsion components and equipment (e.g. motor cases and interstages) for systems specified in 1.A.

Technical Note:
Machines combining the function of spin-forming and flow-forming are, for the purpose of this item, regarded as flow forming machines.

•Austria	•Belgium
•China	•Egypt
•France	•Germany
•India	•Italy
•Japan	•Poland
•Russian Federation	•Spain
•Switzerland	•United Arab Emirates
•United Kingdom	•United States

Global Production



Nature and Purpose: Flow-forming machines capable of producing components for systems specified in 1.A. are large, heavy-duty pieces of manufacturing equipment. Their bases are massive, often requiring a special foundation, in order to support the forming rollers, mandrels and other components and to support the forming forces required without deformation. Power supplies, hydraulic rams and positioning screws are also large enough to resist deflection by the large forming forces.

Method of Operation: Flow-forming machines use a point-deformation process whereby one

or more rollers move along the length of a metal blank, or preform, and press it into a rotating mold or onto a mandrel with the desired shape.

Typical Missile-Related Uses: Flow-forming machines are used to make rocket motor cases, end domes and nozzles.

Other Uses: Flow-forming machines are used to make numerous parts for the aerospace industry, including commercial aircraft parts, tactical missile components and liners for shaped charges. They are also used to make automobile wheels, automatic transmission components for automobiles, gas containers, pressure-tank heads and containers for electronic equipment.

Appearance (as manufactured): Flow-forming machines can be configured either vertically or horizontally. Vertical configurations can form larger parts because they have protruding servo-driven arms to hold the rollers and more horsepower for deformation. Horizontal configurations do not have roller arms as long as those of the vertical machines. An example of a flow-forming machine used to make end domes for propellant tanks is shown in Figure 47 (top right). The related spin-forming process can produce shapes like those made by the flow-forming process. However, spin-forming uses less power to shape the material because it changes the thickness of the material very little from preform to final shape. Specially designed production facilities and equipment resemble aerospace and manufacturing equipment but with attributes designed for a given system.

Appearance (as packaged): Larger vertical machines usually require that roller areas, vertical columns and mandrels be boxed separately in wooden crates for shipping. Smaller vertical machines as well as horizontal machines may be shipped in large wooden containers, with the roller arms shipped in the assembled configuration. They will be securely fastened to the containers to preclude movement. The control unit and any hydraulic supply and power units are also boxed separately for shipment.



Figure 47: ***Top right:*** **A flow-forming machine used to make end domes for propellant tanks. (Aerojet)** ***Bottom right:*** **A horizontal flow-forming machine. (A Handbook for the Nuclear Suppliers Group Dual-Use Annex, Report No. LA-13131-M (April 1996)** ***Left:*** **A vertical flow-forming machine. (Ibid)**

3.C. Materials

3.C.1. 'Interior Lining' usable for rocket motor cases in the subsystems specified in 2.A.1.c.1. or specially designed for subsystems specified in 20.A.1.b.1.

Technical Note:
In 3.C.1. 'interior lining' suited for the bond interface between the solid propellant and the case or insulating liner is usually a liquid polymer based dispersion of refractory or insulating materials e.g. carbon filled HTPB or other polymer with added curing agents to be sprayed or screeded over a case interior.

- Argentina
- Austria
- Azerbaijan
- Belgium
- Brazil
- Canada
- China
- Czech Republic
- France
- Germany
- India
- Iran
- Israel
- Italy
- Japan
- Kazakhstan
- Malaysia
- Netherlands
- New Zealand
- Norway
- Pakistan
- Poland
- Portugal
- Romania
- Russian Federation
- South Africa
- Republic of Korea
- Spain
- Sweden
- Switzerland
- Turkey
- United Kingdom
- United States

Global Production



Nature and Purpose: The interior lining, or liner, is a thin layer of special chemicals used to help the solid propellant adhere to the case insulation. The liner is typically made from elastomers or plastics, and usually is composed of the same binder that is used in the propellant plus additives, such as carbon black, which improve the strength of the liner.

Method of Operation: The lining of a solid propellant rocket motor is a liquid adhesive used to bond the propellant to the insulation. It is often a 10 mm to 20 mm thick layer of a rubbery material applied to the inside of the motor case then partially cured. The freshly mixed (uncured) propellant is then cast into the motor case against this partially cured liner. The cure of both the propellant and the liner is then completed at an elevated temperature.

Typical Missile-Related Uses: All solid propellant rocket motors use lining. The lining bonds the solid propellant to the rocket motor case insulation.

Other Uses: Some materials used in the interior linings of rocket motors are used in military or commercial applications requiring heat-resistant materials.

Appearance (as manufactured): Interior lining is often made from the binder used in the solid propellant mixture without the oxidizer component added (also known as "inhibited propellant"). It is difficult to

identify case insulation from solid propellant without performing various chemical tests on samples of the material.

Appearance (as packaged): Because interior lining is often made from the same binder used in the solid propellant mixture (without the oxidizer component added) and it is used shortly before casting the solid propellant into the motor case, it is not usually packaged for shipment.

3.C.2. 'Insulation' material in bulk form usable for rocket motor cases in the subsystems specified in 2.A.1.c.1. or specially designed for subsystems specified in 20.A.1.b.1.

Technical Note:
In 3.C.2. 'insulation' intended to be applied to the components of a rocket motor, i.e. the case, nozzle inlets, case closures, includes cured or semi-cured compounded rubber sheet stock containing an insulating or refractory material. It may also be incorporated as stress relief boots or flaps specified in 3.A.3.

Nature and Purpose: The main function of insulation is to protect the motor case from combustion products (especially heat) during flight. Case insulation must also meet several secondary objectives. The insulation must mechanically bond the case wall with the propellant. It must also withstand the stresses caused by thermal contraction of the propellant, the weight of the propellant during motor storage and the inertia of the propellant, particularly in upper stages, during acceleration.

Method of Operation: Motor case insulation is sized to allow a maximum amount of propellant in the motor case, but thick enough to protect the case for the anticipated burn time plus a margin of safety. Stress relief flaps, located at the forward and aft end domes are used to prevent case deformations due to high internal pressure. Case deformations in these areas will likely induce stress cracks in either the propellant grain or in the case insulation resulting in motor case failure in flight. Insulation is usually made from elastomers or plastics, and many times the insulation is made of synthetic rubbery material such as ethylene propylene

- Argentina
- Azerbaijan
- Brazil
- China
- France
- India
- Israel
- Japan
- Malaysia
- New Zealand
- Pakistan
- Portugal
- Russian Federation
- Republic of Korea
- Sweden
- Turkey
- United States
- Austria
- Belgium
- Canada
- Czech Republic
- Germany
- Iran
- Italy
- Kazakhstan
- Netherlands
- Norway
- Poland
- Romania
- South Africa
- Spain
- Switzerland
- United Kingdom

Global Production



diene monomer (EPDM), polybutadiene, neoprene or nitrile rubber. Insulation material may contain silica or asbestos and resemble a gray or green sheet of rubber.

Typical Missile-Related Uses: The main purpose of case insulation is to protect the solid propellant rocket motor case from combustion products (especially heat) during flight.

Other Uses: Some materials used in the interior linings or insulation of rocket motors are used in military or commercial applications requiring heat-resistant materials.

Appearance (as manufactured): Internal insulation is a sheet of rubbery substance that is 3 mm to 10 mm thick and up to 1 m in width. Insulation is normally green, gray, dark brown, or black in color.

Appearance (as packaged): Insulation material is shipped in large rolls up to 1.0 m in width and 0.5 m in diameter and sealed in boxes. The solid propellant rocket motor case may or may not have internal insulation in place when shipped.

3.D. Software

3.D.1. "Software" specially designed or modified for the "use" of "production facilities" and flow forming machines specified in 3.B.1. or 3.B.3.

- Austria
- Belgium
- China
- France
- Germany
- India
- Italy
- Japan
- Poland
- Russian Federation
- Republic of Korea
- Spain
- Switzerland
- Sweden
- United Kingdom
- Ukraine
- United States

Global Production



Nature and Purpose: Software controlled under Item 3.D.1. is used to operate the facilities or flow-forming machines used to produce turbojet, turbofan, turboprop, ramjet, and scramjet engines and related components; solid propellant rocket motor cases, insulation components and materials, interior lining materials and nozzles; staging and separating mechanisms and interstage sections; liquid or gel propellant pumps, servo valves, combustion chambers, nozzles and tanks; and specially designed components for hybrid rocket motors.

Method of Operation: Modern machine tools are computer numerically controlled (CNC). A microprocessor in each machine reads the G-Code program that the user creates and performs the programmed operations. Personal computers are used to design the parts and are also used to write programs by either manual typing of G-Code or using Computer Aided Manufacturing (CAM) software that outputs G-Code from the user input of tools and toolpath. CAM generated G-Code programs must be post processed

to the specific machine CNC being employed. Generic G-Code generating programs and libraries are available in the public domain.

Typical Missile-Related Uses: Computer-controlled machine tools are used in the manufacture of liquid propellant rocket engine injectors that have hundreds of small injector elements. CNC Additive Manufacturing (AM) machines are also being used to build injectors and multi-element preburner injectors.

Processes such as diffusion bonding of thin plates use ovens that may be computer-controlled. Plasma spray deposition and other types of material coating such as electroplating use computer-control methods.

Assembly of parts of a liquid propellant rocket engine (injectors to chambers and chambers to nozzles) are typically welded, except for "work-horse" ground test units. Such "orbital" welding (360 degrees around a cylindrical surface) is presently computer-controlled, requiring specially tailored "software".

Inspection of production articles is also increasingly under computer controls. Injectors, for example, contain hundreds of injector holes that must be verified as to size, placement and orientation. Computer-controlled optical comparators are being used to perform this inspection, and specially developed "software" is required.

Other Uses: "Software" used to manufacture MTCR-controlled gas turbine engines, solid propellant rocket motor cases and nozzles, liquid propellant rocket engines, and test equipment can also be used to manufacture products associated with civil and military aircraft and sounding rockets used to study weather and atmospheric conditions at various altitudes. This "software" may also be employed, with modifications, to control other industrial operations.

Appearance (as manufactured): This "software" takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents can contain this "software" and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents containing this "software" are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the "software" is run on the appropriate computer. This "software", including the documentation, is capable of being electronically transmitted over a computer network.

3.D.2. "Software" specially designed or modified for the "use" of equipment specified in 3.A.1., 3.A.2., 3.A.4., 3.A.5., 3.A.6. or 3.A.9.

Notes:
1. "Software" specially designed or modified for the "use" of engines specified in 3.A.1. may be exported as part of a manned aircraft or as replacement "software" therefor.
2. "Software" specially designed or modified for the "use" of propellant control systems specified in 3.A.5. may be exported as part of a satellite or as replacement "software" therefor.

Nature and Purpose: This "software" is used to operate, install, maintain, repair, and overhaul/refurbish turbojet, turbofan and turboprop engines; ramjet/scramjet/pulsejet engines; rocket staging mechanisms, separation mechanisms, and interstage sections; liquid or gel propellant pumps and servo valves; and specially designed components for hybrid rocket motors.

Method of Operation: Before launch, flight "software" described in this section is loaded in the flight computers and flight controllers of rockets and UAVs to control all in-flight activity and operation such as ballistic missile staging. This type of "software" is also used to control the operation of liquid propellant engines and gel propellant motors.

Typical Missile-Related Uses: This "software" is used to turbojet, turbofan and turboprop engines; ramjet/scramjet/pulsejet engines; rocket staging mechanisms, separation mechanisms, and interstage sections; and liquid or gel propellant pumps and servo valves. Often, this type of "software" can automatically initiate malfunction analysis to identify failed components.

Other Uses: N/A.

Appearance (as manufactured): Typically this "software" takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, compact discs, USB flash drives, and documents can contain this "software" and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the "software" is run on the appropriate computer. This "software", including the documentation, is capable of being electronically transmitted over a computer network.

3.D.3. "Software" specially designed or modified for the "development" of equipment specified in 3.A.2., 3.A.3. or 3.A.4.

Nature and Purpose: This "software" is used to research and design ramjet/scramjet/pulsejet engines; solid propellant rocket motor cases with insulation and liners, and nozzles; and rocket staging mechanisms, separation mechanisms, and interstage sections; and to develop pilot production procedures, configuration and integration programs for these items.

Method of Operation: "Software" described in this section is used on computers to develop detailed serial and parallel manufacturing procedures, to design the various components listed in this section, to operate computer controlled machines used to manufacture the various assemblies, and to design, model and test configuration and integration programs for each of these items.

Typical Missile-Related Uses: This "software" is installed on general purpose computers to evaluate the design of, and installed on specialized automated equipment for further development of, ramjet/scramjet/pulsejet engines; solid propellant rocket motor cases with insulation and liners, and nozzles; and rocket staging mechanisms, separation mechanisms, and interstage sections. Usually this task is completed with a series of planning, simulation, flow modeling and other "software" packages. Other "software" in this Item is used to develop the pilot production procedures, configuration and integration programs for these items.

Other Uses: Generally, engineering design software has a very wide variety of uses, while production and development "software" can be used, with modifications, to design and test other detailed operations in large industrial organizations, such as oil production and distribution.

Appearance (as manufactured): Typically this "software" takes the form of a computer program that historically would have been stored on printed, magnetic, optical or other media, but which might also be sold and transferred directly over the internet. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the "software" is run on the appropriate computer. This "software", including the documentation, is capable of being transmitted electronically over a computer network. In the Twenty-first Century, the internet is a very likely means for software transfers across borders.

3.E. Technology

3.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment, materials or "software" specified in 3.A.1., 3.A.2., 3.A.3., 3.A.4., 3.A.5., 3.A.6., 3.A.8., 3.A.9., 3.A.10., 3.B., 3.C. or 3.D.

Nature and Purpose: "Technology" controlled under Item 3.E.1. covers the instructions and knowledge needed to "develop", "produce" or "use" any of the equipment, materials or "software" specified in 3.A.1., 3.A.2., 3.A.3., 3.A.4., 3.A.5., 3.A.6., 3.A.8., 3.A.9., 3.A.10., 3.B., 3.C. or 3.D.

Method of Operation: "Technical assistance" is available in many forms. "Technical assistance" may consist of instruction provided by a person experienced in one or more controlled subjects such as liquid propellant rocket engines, who acts as a trainer in a classroom on or near the production site. A country may receive "technical assistance" from one or more consulting services that specialize in a particular production skill, or in the procurement of technical items or materials. Additionally, a country may receive "technical assistance" by sending students to other countries possessing the technology to attend training and practice the skills necessary to build the required systems. Any manuals and materials received during training may qualify as "technical data."

Typical Missile-Related Uses: With limited exception, "technical assistance" required to build rocket and UAV systems are used only for those purposes. Sounding rockets used in weather research, with minor adjustments, can be converted to ballistic missiles. The "technology" used in each device is very similar.

Other Uses: Some "technology" used to design, manufacture and test UAVs may have functionality in the military or commercial aircraft industry. "Technology" related to flow-forming high strength steel motor cases also has application to commercial and industrial heat exchanger production.

Appearance (as manufactured): N/A

Appearance (as packaged): N/A

Category II - Item 4

Propellants, Chemicals and Propellant Production

Category II – Item 4: Propellants, Chemicals and Propellant Production

4.A. Equipment, Assemblies and Components

None.

4.B. Test and Production Equipment

4.B.1. "Production equipment", and specially designed components therefor, for the "production", handling or acceptance testing of liquid propellants or propellant constituents specified in 4.C.

•Argentina	•Australia
•Austria	•Beligum
•Brazil	•Bulgaria
•Canada	•China
•Czech Republic	•Egypt
•Finland	•France
•Germany	•Greece
•India	•Iran
•Israel	•Japan
•North Korea	•Pakistan
•Poland	•Russian Federation
•Slovak Republic	•South Africa
•Republic of Korea	•Spain
•Sweden	•Ukraine
•United Kingdom	•United States

Global production



Nature and Purpose: Individual components of liquid propellant production equipment are common to any petroleum distillation facility or large chemical plant. Typical components include reactor tanks, condensers, recovery columns, heaters, evaporators, filter assemblies, decanters, chillers, gas separators, and centrifugal pumps. None of these components by themselves are specially designed for use in making liquid propellants. However, when combined into a propellant production facility, such a facility is generally optimized for the production of a particular propellant and ill-suited for making anything else.

The technologies for making liquid propellants are generally well known, although various companies may have proprietary procedures for maximizing yield, minimizing cost, or finding alternative uses for byproducts.

Acceptance testing of liquid propellants requires analytical equipment common to most chemical quality control labs, including equipment such as gas chromatographs, atomic absorption spectrometers, infrared spectrometers, and bomb calorimeters. This equipment generally can be used without modification to analyze liquid rocket propellants for acceptance.

Method of Operation: Specific production methods depend on the propellant being manufactured. Many of the constituents used in liquid propellants are commonly produced for commercial purposes but require additional processing to purify, stabilize, inhibit, or blend to achieve certain properties. For example, sulfuric acid or magnesium carbonate is used to purify nitric acid. Commercial nitric acid, usually combined with water as hydrate, contains only 55% to 70% acid. Chemical processing is needed to break the hydrates to produce 97% to 99% pure, anhydrous (waterless) nitric acid. To form Inhibited Red Fuming Nitric Acid (IRFNA), N_2O_4 is added to the concentrated nitric acid to stabilize it against rapid decomposition, and trace amounts of hydrogen fluoride (HF) are added to reduce corrosion of containers.

Typical Missile-Related Uses: Liquid propellant production and acceptance testing equipment are required to develop an indigenous capability to make propellants.

Other Uses: The equipment and technologies are in common use and widely known in the petroleum and chemical production industries.

Appearance (as manufactured): In general, complete liquid propellant manufacturing facilities are not bought and transferred in one piece; they are assembled from many common pieces of chemical and industrial process equipment. Unless a turnkey plant is shipped, the most likely encountered items are probably the plans, drawings, calculations, and equipment lists associated with a plant design. There is even commercially available software that assists chemical engineers in designing such facilities.

Appearance (as packaged): The size of liquid propellant manufacturing equipment dictates the packaging. Smaller machines are crated in shock-absorbing containers or attached to cushioned pallets isolated from other packages. Larger machines are disassembled for shipping and reassembled onsite and their components are packaged separately in crates or pallets.

4.B.2. "Production equipment", other than that described in 4.B.3., and specially designed components therefor, for the production, handling, mixing, curing, casting, pressing, machining, extruding or acceptance testing of solid propellants or propellant constituents specified in 4.C.



Figure 48: A propellant casting mandrel. (ATK)

Nature and Purpose: The production equipment and infrastructure necessary to produce solid rocket propellant are complex and specialized. Facilities and equipment are necessary for preparing the various propellant ingredients, mixing and handling the propellant, casting and curing the propellant inside the motor case, and other specialized operations such as pressing, machining, extruding, and acceptance testing.

Method of Operation: Solid propellant is produced by one of two processes, either batch mixing or continuous mixing. Most missile programs use the batch process to make solid rocket motor propellant. After receipt and acceptance testing of the individual ingredients, ammonium perchlorate (AP) is usually ground in a fluid energy mill to obtain the required particle size. All ingredients, including the binder, AP, metal powder, stabilizers, curing agents, and burn-rate modifiers, are mixed in large mixers to form a viscous slurry. The propellant slurry is poured or cast into the rocket motor case (Figure 49), in which a mandrel (see Figure 48) creates a hollow chamber running down the center of the motor. The loaded motor case is placed in a large oven to cure the propellant. During curing, the slurry is transformed into a hard rubbery material called propellant grain. The rocket motor with the cured propellant is then cooled, the mandrel removed, and any final trimming or machining operations completed. Finished motors are usually X-rayed (Figure 50) to ensure that the propellant grain is homogeneous, bonded everywhere to the case, and free of cracks. Additional Non-Destructive Testing (NDT) methods such as longitudinal beam ultrasonic pulse-echo may be used to check the bond-line integrity between the case and insulation layer.


Figure 49: Solid propellant in liquid form is poured into rocket casings and cast into the required shape. The casting is moved by a hydraulic mount to remove bubbles or other defects. (ATK)

In continuous mixing, the same propellant ingredients are continuously measured into a mixing chamber, mixed, and continuously discharged into the motor or other container until the required amount of propellant has been obtained. This type of mixing is difficult because it is hard to precisely measure small amounts of some ingredients such as curing agents required for some propellant mixtures. Continuous mixing is not, therefore, used to any large extent.

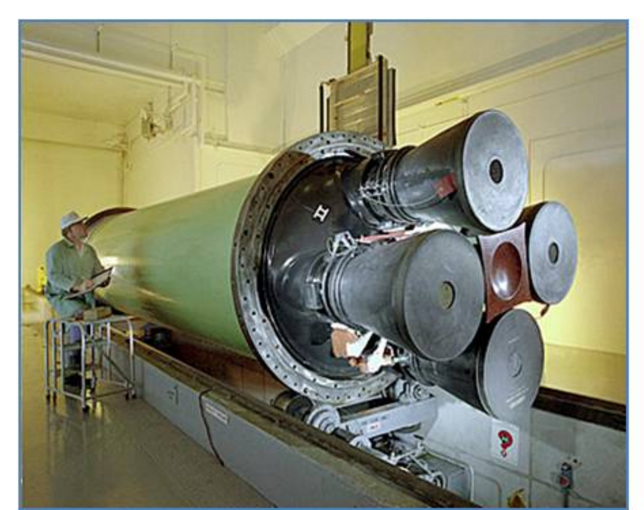




Figure 50: A finished motors being X-rayed to ensure that the propellant grain is homogeneous, bonded to the case, and free from cracks and other imperfections. (ATK)

Typical Missile-Related Uses: Better solid propellants improve missile range and payload capability. Solid propellant production equipment and acceptance testing equipment are required for a nation to develop an indigenous capability to produce propellants for rocket-motor-powered missiles.

Other Uses: N/A

Appearance (as manufactured): Specialized devices are used to cast propellant by creating a vacuum, which removes air from the propellant as it is poured into the rocket motor case. The size of these devices varies with the size of the rocket motors, but principles of operation are the same. The equipment and process for a small motor are shown in Figure 4. The mixed propellant is poured from the mix bowl into a large casting funnel that is attached to the rocket motor. A large valve in the neck of the casting funnel isolates the motor in the vacuum from ambient atmospheric conditions. Once the casting funnel is full of propellant, the valve is opened slowly to allow the propellant to flow into the rocket motor case. Motors are sometimes cast in a cast/cure pit, which is an underground concrete structure lined with heating coils. The entire pit is evacuated before casting operations start. As with other specialized propellant equipment, the casting equipment is generally constructed on-site; its size depends on the size of the motor and the manner in which the casting operation is done.

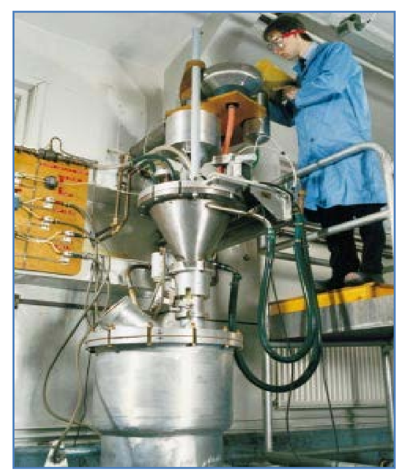
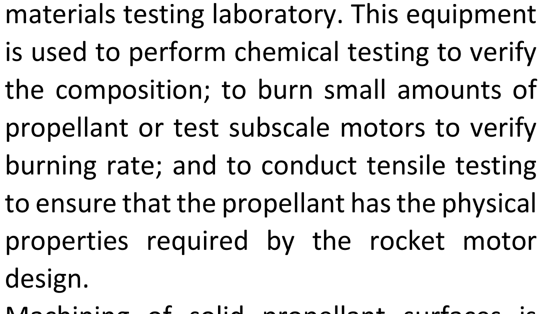


Figure 51: Slurry cast double-base mixing equipment for small motor. (British Aerospace Limited)

Curing equipment ranges in size from large, electrically or steam-heated ovens, to large heated buildings. This equipment is not particularly specialized because the process is a simple one, requiring only that motor temperature be raised for a given amount of time. Large cast/cure pits are permanent, on-site facilities.

The equipment used for acceptance testing of a batch of propellant is identical to the equipment found in an analytical chemistry or a



- Argentina
- Brazil
- China
- Finland
- Germany
- Iran
- Israel
- Japan
- Pakistan
- South Africa
- Spain
- Switzerland
- Ukraine
- United States
- Beligum
- Canada
- Egypt
- France
- India
- Ireland
- Italy
- Netherlands
- Russian Federation
- Republic of Korea
- Sweden
- Syria
- United Kingdom



materials testing laboratory. This equipment is used to perform chemical testing to verify the composition; to burn small amounts of propellant or test subscale motors to verify burning rate; and to conduct tensile testing to ensure that the propellant has the physical properties required by the rocket motor design.
Machining of solid propellant surfaces is generally done by large cutting machines specially modified to accommodate the safety hazards associated with solid propellants. Many of these types of machines are built specifically for a particular rocket motor.

Solid propellant grains for the large rocket motors of interest are usually too large to be directly handled by an extruder. However, some propellants of MTCR interest are extruded in a preliminary processing step. Extrusion is generally limited to propellant grains less than 0.3 m in diameter and has more application to tactical air-to-air, surface-to-air, and air-to-surface missiles.

Appearance (as packaged): The size of solid propellant production equipment dictates their packaging. Smaller machines are crated in shock-absorbing containers or attached to cushioned pallets. Larger machines are disassembled for shipping and reassembled onsite. Their components are packaged separately in crates or on pallets.

4.B.3. Equipment as follows, and specially designed components therefor:

a. Batch mixers with provision for mixing under vacuum in the range of zero to 13.326 kPa and with temperature control capability of the mixing chamber and having all of the following:

1. A total volumetric capacity of 110 litres or more; and
2. At least one 'mixing/kneading shaft' mounted off centre;

Note:
In Item 4.B.3.a.2. the term 'mixing/kneading shaft' does not refer to deagglomerators or knife-spindles.

b. Continuous mixers with provision for mixing under vacuum in the range of zero to 13.326 kPa and with a temperature control capability of the mixing chamber and having any of the following:

1. Two or more mixing/kneading shafts; or
2. A single rotating shaft which oscillates and having kneading teeth/pins on the shaft as well as inside the casing of the mixing chamber;

- Argentina
- Brazil
- China
- France
- Germany
- India
- Iran
- Israel
- Japan
- Pakistan
- Russian Federation
- United Kingdom
- United States

Global production



Nature and Purpose: Batch mixers are powerful mixing machines for batch quantities of very viscous material. They are derived from machines used to mix bread dough. Their purpose is to mix liquids and powders of differing densities into a uniform blend.

Continuous mixers are powerful mixing machines that operate in a flow-through manner. They mix larger quantities than batch mixers for high volume production.

Method of Operation: Batch mixers operate much like a household electric mixer. The bowl holds the ingredients that may be added in sequence while the turning blades mix everything together. Temperature control and vacuum are maintained by surrounding the bowl with a water jacket and by covering the bowl with a sealed lid (Figure 52).

Continuous mixers gradually feed all the ingredients simultaneously in their correct proportions through the mix region. The mixing/kneading shafts thoroughly mix the continuous flow of liquids and powders, and the uniform blend is gradually discharged from the large pipe in a steady viscous stream.

Typical Missile-Related Uses: Batch and continuous mixers are used to mix precise quantities of liquid and powdered propellant constituents into a very uniform blend. This mixture will burn violently if ignited



Figure 52: A 420-gallon propellant mixing bowl. (ATK)

so safety procedures are critical. The blend produced is later cast and cured in another process to create a rubbery composite material that serves as the propellant in a solid propellant rocket motor.

Other Uses: Batch and continuous mixers may be used whenever the production of a viscous blend is required. However, most commercial applications will not require the temperature control and vacuum capabilities specified in Item 4.B.3.

Appearance (as manufactured): The most distinctive components of a batch mixer are the mixing bowl and the mix blade assembly. The mixing bowls are typically 0.75 m to 1.5 m deep and 1 to 2 m in diameter, as shown in Figure 53, but may be significantly larger for mixers greater than 450 gallons (1,700 l). They are double-wall constructed; the inner wall is made of highly polished stainless steel, and the outer wall is generally made of cold-rolled steel, sometimes painted. The space between the walls is used for a hot/cold water heating/cooling jacket. The outer wall has two valves for the connection of inlet/outlet water hoses. The bowl is generally welded to a thick steel rectangular plate with wheels at each corner. The wheels may have grooves so that the bowl assembly can be placed on rails for easier movement.



Figure 53: Solid propellant being mixed in a 600-gallon vertical planetary mixer. (Thiokol Corp.)

Sometimes the upper rim of the bowl is a machined flat surface with a large groove to accommodate an O-ring (gasket); other times the mixer head is provided with one or more such grooves. The purpose of the O-ring is to provide a seal while the mixing operation is under vacuum. The blade assembly consists of two or three large blades, also made of highly polished stainless steel. Most assemblies use twisted-paddle blades where one of the blades sometimes has an opening. Other assemblies use cork-screw-shaped blades. Although it is not evident in the shipping configuration, the blade assembly operates in a "planetary" manner; that is, the central blade rotates in a fixed position while the other one or two blades rotate about their own axes as well as rotating about the central fixed blade. The remaining mixer components include an electric motor, gear assembly, mixer head, and supporting structure.

Appearance (as packaged): Mixers may be shipped as complete units or as components. As precision-machined devices, mixer blades are packaged to protect them from damage and the shipping environment. They are likely to be incorporated into the mixer head and frame assembly and securely cradled in shock isolation material blocking during shipping. Mixing bowls are large, heavy pieces of equipment also likely to be shipped in large, strong, wooden crates. They are securely attached to the crates to avoid damage. Crates tend to lack any distinctive features or markings.

4.B.3.c. Fluid energy mills usable for grinding or milling substances specified in 4.C.;

- Australia
- Belgium
- China
- France
- Germany
- India
- Italy
- Japan
- Luxembourg
- Netherlands
- New Zealand
- Russian Federation
- South Africa
- Spain
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: Fluid energy mills (often referred to as jet mills) use high-pressure air or inert gas to cause particles to impact against one another. These impacts fracture the material into smaller pieces until a minimum particle size is obtained. Particles below the minimum size exit the mill while larger particles continue the milling process. The resulting milled product has a tight size distribution with typical particle size less than 20 microns. Particle sizes in this range are not easily obtained by mechanical grinding processes which have a lower size limit of 44 microns (325 mesh). Fluid energy mills are also much safer for grinding explosive materials such as HMX and RDX.

Typical Missile-Related Uses: Fluid energy mills produce fine-grained AP, HMX, or RDX powders used as oxidizers or burn-rate modifiers for solid rocket propellant.

Other Uses: Fluid energy mills are also used in food, pharmaceutical, mining, and paint pigment industries.

Appearance (as manufactured): Fluid energy mills are extremely simple devices with no moving parts. Most are flat, cylindrical devices made of stainless steel and measuring 7 cm to 10 cm in height and 7 cm to 40 cm in diameter. They have an inlet and outlet port for the attachment of ancillary equipment such as material supply hoppers, gas inlets and product separation cyclones which remove the milled product from the gas stream.

Appearance (as packaged): Fluid energy mills (Figure 54) are generally shipped in wooden crates with foam or packing material used to protect them during shipment. The crates are not distinctive.





Figure 54: Examples of various fluid energy mills. (The Jet Pulverizer Company)

4.B.3.d. Metal powder "production equipment" usable for the "production", in a controlled environment, of spherical or atomised materials specified in 4.C.2.c., 4.C.2.d. or 4.C.2.e.

Note:
4.B.3.d. includes:
a. Plasma generators (high frequency arc-jet) usable for obtaining sputtered or spherical metallic powders with organisation of the process in an argon-water environment;
b. Electroburst equipment usable for obtaining sputtered or spherical metallic powders with organisation of the process in an argon-water environment;
c. Equipment usable for the "production" of spherical aluminum powders by powdering a melt in an inert medium (e.g. nitrogen).

Note:
1. The only batch mixers, continuous mixers, usable for solid propellants or propellants constituents specified in 4.C., and fluid energy mills specified in 4.B., are those specified in 4.B.3.

2. Forms of metal powder "production equipment" not specified in 4.B.3.d. are to be evaluated in accordance with 4.B.2.

Method of Operation: The most common approach for producing fine metal powders for use as constituents in missile propellants is the molten metal process using equipment specified in subparagraph c of the Note to Item 4.B.3.d. above. This process (also called gas atomization) scales well and can be used to make large amounts of powdered metal cost effectively. Both the plasma generator and electro-burst methods are relatively new in the application and are not in widespread use on production programs. They are currently considered laboratory or R&D processes, whereas the molten metal process is fully developed for large scale production applications.

Typical Missile-Related Uses: Atomized and spherical metallic powder production equipment is used to produce uniform, fine-grained metal powders used as a constituent in solid and liquid rocket fuel. Metallic powder is used to enhance the performance characteristics of the motor/engine. Powdered metals are

crucial in modern composite solid propellant motors. Atomized and spherical metallic powders in missile propellant provides greater thrust resulting in greater missile range and payload capability.

Other Uses: Atomized and spherical metallic powder production equipment may be used to produce metal powders for many commercial applications, from pigments in metallic paints to feedstock for additive manufacturing machines.

Appearance (as manufactured): Equipment to produce atomized, spherical metal powder via the method described above is readily assembled from common industrial equipment. The equipment includes a furnace to melt the material; a sprayer/nozzle/crucible assembly that injects the metal into the tank; a large chiller tank into which the liquid metal is sprayed; a pump attached to the tank to remove the air; a filling system for the inert gas (e.g., tanks and a valve); a cyclone separation unit; a dust collector; and a product storage tank.

Appearance (as packaged): Production equipment for atomized metal powders is not shipped as a single unit. Instead, its components are disassembled, packaged, and shipped like most industrial equipment. Smaller pieces are boxed or crated and secured to a pallet. The tank is boxed to protect it from denting. Spray nozzles are packaged separately in protected boxes.

4.C. Materials

4.C.1. Composite and composite modified double base propellants.

Nature and Purpose: Composite propellants are mixtures of separate oxidizer and fuel substances, both particulate solids (e.g. powder or crystals), held together by a rubbery material referred to as the binder (Figure 55). They provide a chemically stable, structurally robust, storable, high-performance, solid propellant for rocket motors. Composite modified double base propellants (CMDB) may be either composite propellants with some double base ingredients, or double base propellants with some composite ingredients. The term CMDB can also refer to composite propellants in which the binder is a highly energetic double-base type material. Double base substances essentially have fuel and oxidizer on different parts of the same molecule, such as nitrocellulose and nitroglycerine.



Figure 55: Composite propellants manufactured for use in rocket motors. (Daicel Chemical Industries, Ltd)

Method of Operation: Selected binders, fuels, and oxidizers are mixed in particular ratios and cast (poured and then solidified) directly into rocket motor casings or into a mold for subsequent insertion into a case (cartridge loaded). For either method, the cylindrical block of solid propellant is referred to as the propellant grain. Inside a solid rocket motor, the grain typically has a central open area where combustion takes place. Alternatively there are end-burning grains. When ignited, the propellant grain burns at its exposed surface area (internal or end only), while the outside of the grain is bonded to the case to avoid

- Argentina
- Brazil
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- North Korea
- Norway
- Pakistan
- Republic of Korea
- Russian Federation
- Spain
- Sweden
- Switzerland
- Taiwan
- United Kingdom
- United States

Global production



combustion on its outer surface. The result is steady production of high-pressure, high-temperature exhaust gases that escape at extremely high speeds to provide thrust. Once ignited, solid propellant cannot be readily throttled or extinguished because it burns without air and at very high temperatures.

Typical Missile-Related Uses: Composite and composite modified double-base propellants are used to provide the propulsive energy for many rocket systems including stages for ballistic missiles and space launch vehicles, and for booster motors for launching cruise missiles and other unmanned aerial vehicles (UAVs).

Other Uses: On a smaller scale, solid propellants are also used in tactical missiles and sometimes for satellites and spacecraft. Orbit raising from geosynchronous transfer orbit (GTO) to geostationary earth orbit (GEO) has sometimes been accomplished with solid propellant using "apogee kick motors." Space applications have also included unmanned lunar landing (Surveyor circa 1965), and orbit insertion at Venus (Magellan 1989).

Appearance (as manufactured): Typically solid propellant is cast into grains shortly after mixing, so the manufactured appearance is either a grain alone or a grain inside a cylindrical rocket motor case, the latter usually having a conical nozzle at one end to make a complete solid rocket motor. Considering the grain alone, composite and composite modified double-base propellants are hard, rubbery materials resembling automobile tires in texture and appearance (Figure 56). Ingredients such as aluminum or another metal powder impart a dark gray color; however, other additives – included to control ballistic and mechanical properties, as well as to ensure chemical stability – may cause the color to vary (from red to green to brown to black).

Appearance (as packaged): Once the components of the propellants are mixed together, they are poured directly into the motor case (itself typically the outer wall of a missile stage) and solidify into a single piece of material to form a completed grain inside the motor. Thus, these propellants are shipped only as the major internal component in a loaded rocket motor and usually are not encountered separately from a motor case. Exceptions are cartridge-loaded systems that fit a cartridge of propellant into a motor case, typically only done for small motors.



Figure 56: A sample of double-base rocket motor propellant. (Bayern-Chemie GmbH)

Solid rocket motors for use on spacecraft need to maximize the propellant quantity relative to the mass of the case. Therefore, such solid rocket motors are nearly spherical in shape rather than cylindrical because aerodynamics is not a concern in space (no advantage to being long and narrow).

Additional Information: The most commonly used fuel component of composite propellants is aluminum powder, which has better performance and a greater ease of use than other metal powders that may be used. The oxidizer component of choice is ammonium perchlorate (AP); other oxidizers are non-aluminum metal perchlorates, ammonium nitrate (AN), and ammonium dinitramide (ADN).

The use of metal perchlorates or AN greatly decrease performance and thus have only limited use in specialized propellants. ADN is a newer oxidizer than AP, with better performance than AP, but it has limited availability and is more difficult to work with. The high explosives HMX and RDX may be used as an adjunct to AP in order to increase propellant performance. The binder used in composite propellants is normally a synthetic rubber; the best one is hydroxyl-terminated polybutadiene (HTPB). Other binders are carboxy-terminated polybutadiene (CTPB), polybutadiene-acrylic acid polymer (PBAA), or polybutadiene-acrylic acid-acrylonitrile terpolymer (PBAN). Elastomeric polyesters and polyethers such as polypropylene glycol may also be used as binders. Composite modified double-base propellant also uses nitrocellulose plasticized with nitroglycerine or other nitrate esters as a binder system.

4.C.2. Fuel Substances as follows:
a. Hydrazine (CAS 302-01-2) with a concentration of more than 70%;
b. Hydrazine derivatives as follows:

1. Monomethylhydrazine (MMH) (CAS 60-34-4);
2. Unsymmetrical dimethylhydrazine (UDMH) (CAS 57-14-7);
3. Hydrazine mononitrate (CAS 13464-97-6);
4. Trimethylhydrazine (CAS 1741-01-1);
5. Tetramethylhydrazine (CAS 6415-12-9);
6. N,N diallylhydrazine (CAS 5164-11-4);
7. Allylhydrazine (CAS 7422-78-8);
8. Ethylene dihydrazine (CAS 6068-98-0);
9. Monomethylhydrazine dinitrate;
10. Unsymmetrical dimethylhydrazine nitrate;
11. Hydrazinium azide (CAS 14546-44-2);
12. 1.1-Dimethylhydrazinium azide (CAS 227955-52-4) / 1,2-Dimethylhydrazinium azide (CAS 299177-50-7);
13. Hydrazinium dinitrate (CAS 13464-98-7);
14. Diimido oxalic acid dihydrazine (CAS 3457-37-2);
15. 2-hydroxyethylhydrazine nitrate (HEHN);
16. Hydrazinium perchlorate (CAS 27978-54-7);
17. Hydrazinium diperchlorate (CAS 13812-39-0);
18. Methylhydrazine nitrate (MHN) (CAS 29674-96-2);
19. 1.1-Diethylhydrazine nitrate (DEHN) / 1.2-Diethylhydrazine nitrate (DEHN) (CAS 363453-17-2);
20. 3,6-dihydrazino tetrazine nitrate (DHTN);

Technical Note:
3,6-dihydrazino tetrazine nitrate is also referred to as 1,4-dihydrazine nitrate.

Nature and Purpose: Hydrazine, MMH, and UDMH are liquid rocket fuels. They are used in a wide variety of liquid propellant rocket engines requiring high performance and long storage times. All three are referred to as “storable” because they remain liquid at room temperature and atmospheric pressure (unlike liquid hydrogen fuel for example). Hydrazine is widely used as a monopropellant (without an oxidizer) by decomposing it into hot gases (hydrogen, nitrogen, and ammonia) with a catalyst. Hydrazine has been mixed with MMH or UDMH fuels in order to improve performance.

Method of Operation: The hydrazine family of fuels is hypergolic (self-igniting) upon contact with various oxidizers such as nitrogen tetroxide, nitric acid, chlorine, or fluorine. When used in a bipropellant system, hydrazine releases about half of its energy by decomposing into a hot gas and half by burning the resulting hydrogen with an oxidizer.

- Brazil
- China
- France
- Germany
- Russian Federation
- United Kingdom
- United States

Global production



Typical Missile-Related Uses: Plain hydrazine (N_2H_4) is sometimes referred to as "neat hydrazine" in order to distinguish it from MMH, UDMH, mixtures, and water dilutions. Although neat hydrazine can be burned with an oxidizer, safe combustion is more challenging than with MMH, for example. While hydrazine has a higher energy performance than MMH and UDMH, it freezes more readily than water. MMH and UDMH are preferred missile fuels due to better combustion stability and because they remain liquid over a much wider temperature range, e.g. minus 50 °C to plus 70 °C. Including hydrazine in mixtures improves the energy performance without sacrificing the storage temperature range. Other substances listed under MTCR 4.C.2.b. can also be used in fuel mixtures for various reasons.

Hydrazine, MMH and UDMH are widely used in combination with nitrogen tetroxide, (N_2O_4 or "NTO") in bipropellant rocket engines. One practical consideration is that the desired ratio for MMH and NTO permits equal sized tanks to be used for the fuel and oxidizer.

The reactions of methylated and other allylated hydrazines with N_2O_4 under ideal conditions should yield CO_2, N_2 and H_2O. However, complete combustion is rarely, if ever, achieved in actual engine firings. For a variety of reasons including valve timing and imperfect contact between fuel and oxidizer injector sprays, combustion is less complete during pulse-mode (on-off) operation of bipropellant rocket engines, as is needed for precise maneuvering. Also during pulse-mode operation, average combustion chamber temperatures are lower which also contributes to incomplete combustion.

Other Uses: Hydrazine is the current and most common propellant for small monopropellant catalytic thrusters for spacecraft attitude control and minor satellite maneuvers. Large velocity changes for satellites use oxidizer along with MMH, UDMH, or a hydrazine fuel mixture. Hydrazine is also used in electrolytic plating of metals on glass and plastics, pharmaceuticals, fuel cells, dyes, photographic chemicals, and agricultural chemicals, and as a polymerization catalyst and a corrosion inhibitor in boiler feed water (water treatment) and reactor cooling water. MMH is used in aircraft emergency power units.

Appearance (as manufactured): Hydrazine is a clear liquid with a freezing point slightly above that of water, at about 2 °C, and a normal boiling point of 114 °C. Its density is slightly greater than that of water, at 1.003 g/cc. It is irritating to the skin, eyes, and lungs, and is highly toxic when ingested. MMH is a clear liquid with a freezing point of –52 °C and a normal boiling point of 88 °C. These features make it an attractive fuel for tactical military missiles. It has a lower density of 0.87 g/cc and is also highly toxic. UDMH, similarly toxic, is a clear liquid with a freezing point of –57 °C and a normal boiling point of 62 °C. Its density is 0.78 g/cc.



Figure 57: 34-gallon anhydrous hydrazine shipping containers made of 300-series stainless steel. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))

Appearance (as packaged): Anhydrous (water eliminated) hydrazine, MMH, and UDMH are classified as flammable liquids and poisons. Hydrazine products can be stored and shipped in barrels or tanks made of aluminum, 300-series stainless steel, and titanium alloys. Small purchases are commonly packed in portable drums, while larger orders are shipped in railroad tank cars. Containers of fuel in the hydrazine family have all air replaced with an inert gas such as nitrogen to prevent contamination and slow oxidation. If properly labeled (Figure 57), containers should specify “flammable” and have numerical information such as United Nations designations for international hazardous shipments. Examples of the latter numbers are UN 2029, UN 1244, and UN 1163, respectively, for anhydrous hydrazine, MMH, and UDMH. There is also a system of Chemical Abstracts Service (CAS) registry numbers.

4.C.2.c. Spherical or spheroidal aluminium powder (CAS 7429-90-5) in particle size of less than 200 x 10^{-6} m (200 µm) and an aluminium content of 97% by weight or more, if at least 10% of the total weight is made up of particles of less than 63 µm, according to ISO 2591-1:1988 or national equivalents;

Technical Note:
A particle size of 63 µm (ISO R-565) corresponds to 250 mesh (Tyler) or 230 mesh (ASTM standard E-11).

4.C.2.d. Metal powders of any of the following: zirconium (*CAS 7440-67-7*), beryllium (*CAS 7440-41-7*), magnesium (*CAS 7439-95-4*) or alloys of these, if at least 90% of the total particles by particle volume or weight are made up of particles of less than 60 µm (determined by measurement techniques such as using a sieve, laser diffraction or optical scanning), whether spherical, atomised, spheroidal, flaked or ground, consisting of 97% by weight or more of any of the above mentioned metals;

Note:
In a multimodal particle distribution (e.g. mixtures of different grain sizes) in which one or more modes are controlled, the entire powder mixture is controlled.

Technical Note:
The natural content of hafnium (CAS 7440-58-6) in the zirconium (typically 2% to 7%) is counted with the zirconium.

4.C.2.e. Metal powders of either boron (CAS 7440-42-8) or boron alloys with a boron content of 85% or more by weight, if at least 90% of the total particles by particle volume or weight are made up of particles of less than 60 µm (determined by measurement techniques such as using a sieve, laser diffraction or optical scanning), whether spherical, atomised, spheroidal, flaked or ground;

Note:
In a multimodal particle distribution (e.g. mixtures of different grain sizes) in which one or more modes are controlled, the entire powder mixture is controlled.

4.C.2.f. High energy density materials, usable in the systems specified in 1.A. or 19.A., as follows:

1. Mixed fuels that incorporate both solid and liquid fuels, such as boron slurry, having a mass- based energy density of 40 x 10^6 J/kg or greater;
2. Other high energy density fuels and fuel additives (e.g., cubane, ionic solutions, JP-10) having a volume-based energy density of 37.5 x 10^9 J/m^3 or greater, measured at 20°C and one atmosphere (101.325 kPa) pressure.

Note:
Item 4.C.2.f.2. does not control fossil refined fuels and biofuels produced from vegetables, including fuels for engines certified for use in civil aviation, unless specifically formulated for systems specified in 1.A. or 19.A.



Nature and Purpose: The metals aluminum, beryllium, boron, magnesium, and zirconium are good fuels in particle sizes less than 60 x 10^{-6} m (60 µm).They are used as a constituent fuel to enhance solid and liquid rocket propellant performance. For example, aluminum powder as a fuel additive makes up 5% to 21% by weight of solid propellant. Combustion of the aluminum fuel increases the propellant flame temperature by up to 800 °K and increases specific impulse by as much as 10%.

Method of Operation: Metal powder is added to either the solid propellant grain during rocket motor production or to liquid rocket fuel to form a slurry. Because the surface-to-volume ratio of such small metal particles is very high, the oxidizer envelops and quickly burns each metal particle, thereby releasing high energy per weight at very high temperature. There are also high energy density fuels and fuel additives formulated for missile uses that do not use metal powders.

Typical Missile-Related Uses: Aluminum powder is relatively inexpensive and is widely used as a fuel component in solid and liquid rocket motors/engines to increase the specific impulse of the propellant and to help stabilize combustion. Beryllium, boron, magnesium, and zirconium metal fuels may also be used, but in practice they have few military missile-related uses. In general, they are expensive, dangerous to handle, and difficult to control. Beryllium motors have been developed only as upper stages because some of their exhaust products are toxic.

Some high energy density fuels are formulated specifically for missile applications, such as Jet Propellant 10 (JP-10) for use in volume-constrained cruise missiles, and certain formulations of kerosene for use as rocket fuel. Other high energy density materials, such as cubane or quadracyclane, may be used as a fuel additive to gain more seconds of specific impulse for existing rocket systems and propellants but they are both hard to synthesize and expensive to produce in quantity.

Other Uses: Aluminum powder is used as a main ingredient in aluminum spray paint. Spherical aluminum powder is used as a catalyst and as a component in coatings for turbine shells, in construction materials like foamed concrete and as a feedstock for additive manufacturing machines. Magnesium is used primarily in the pyrotechnics industry. Boron is sometimes used in fuel slurry for ducted rockets and solid-fuel ramjets for tactical missiles. Zirconium has been used in some high-density composite propellants for volume limited tactical applications. Both boron and zirconium are used in ignition compounds for igniters.

Appearance (as manufactured): Aluminum powder is a gray or dull silver powder. The particle size of most propellant grade aluminum powder ranges from 3 to 100 microns, although larger sizes have been used. The particle shape is more or less spherical. Beryllium, magnesium, and zirconium are also gray or dull silver powders. Boron is a dark brown powder. The appearance of boron slurry depends on the liquid

to which it is added and the boron particle size; typically, the color is dark brown or black. For example, boron mixed with dicyclopentadiene is a potential ramjet fuel and forms a chocolate-brown slurry with the consistency of honey. Missile fuels, such as Rocket Propellant 1 (RP-1) and JP-10, are similar in appearance to jet fuels which are clear to amber colored liquids.

Appearance (as packaged): Aluminum powder is generally packaged and shipped in steel drums with a capacity of 30 gallons or less. Aluminum powder in a 30-gallon drum weighs approximately 180 kg. The other metals, though much less likely to be encountered, are packaged similarly. Missile fuels, such as JP-10 and RP-1, may be packaged and shipped in 55-gallon drums. Given the large quantities of RP-1 used in rocket systems, it may also be transported in large 7,000 gallon capacity tanker trailers.

Additional Information: Aluminum has a density of 2.7 g/cc, but its bulk density is somewhat less, depending on particle size. Beryllium and its combustion products are very toxic. Boron is difficult to ignite. Zirconium is very dangerous to handle in finely powdered form because it spontaneously ignites in air; thus, it is usually shipped in water.

4.C.2.g. Hydrazine replacement fuels as follows:
1. 2-Dimethylaminoethylazide (DMAZ) (*CAS 86147-04-8*).

Nature and Purpose: Given the widespread usage of hydrazine and its derivatives, the health hazards of these fuels have motivated much research toward propellants having similar energetic performance and physical properties, while being less hazardous to people upon exposure (vapor inhalation or skin contact).

For bipropellant rocket propulsion, 2-dimethylaminoethylazide (DMAZ) has attracted much attention as a potential replacement for monomethyl hydrazine (MMH) and unsymmetrical dimethyl hydrazine (UDMH). DMAZ has a density very close to that of water, along with a low freezing point (minus 69 °C) and a high boiling point (135 °C).

Other substances have been studied as nontoxic replacements for neat hydrazine, for monopropellant propulsion. One kind of alternative consists of solid energetic materials dissolved in water. An example of the latter is hydroxyl ammonium nitrate (HAN), which has been the subject of much experimentation, but is not controlled under Item 4.C.2.g.

Method of Operation: DMAZ would be used much like MMH and UDMH. DMAZ would be combined in a liquid propulsion system with a storable oxidizer such as NTO or IRFNA (see MTCR Item 4.C.4.).

Typical Missile-Related Uses: Missile-related uses for DMAZ would be essentially the same as for MMH or UDMH (MTCR Item 4.C.2.b.).

Other Uses: N/A.

Appearance (as manufactured): DMAZ is a colorless liquid.

Appearance (as packaged): DMAZ would be packaged in drums and labeled as a combustible liquid.

4.C.3. Oxidizers/Fuels as follows:
Perchlorates, chlorates or chromates mixed with powdered metals or other high energy fuel components.

Nature and Purpose: Perchlorates, chlorates, and chromates mixed with fuel components of any kind (e.g., powdered metals) are extremely unstable and have the potential to ignite or explode. AP, the oxidizer of choice for most solid propellant applications, is rarely shipped in large bulk quantities mixed with a fuel component because of the associated combustion hazard. However, these mixtures are shipped in components such as igniters or in small packages (approximately 3 kg).

- There are no known suppliers of these mixtures because of the extreme fire hazard; however, many countries can create and ship such mixtures.

Global production



Method of Operation: The oxygen in perchlorates, chlorates, and chromates is released during combustion, making it available to burn the high-energy fuel in the propellant mixture. Because the oxygen is distributed evenly throughout the mixture, it burns very rapidly without air and cannot be extinguished once ignited.

Typical Missile-Related Uses: AP mixed with powdered aluminum is routinely used in solid rocket motors. Other mixtures of oxidizers and fuels are generally used in missile ignition or delay devices and are rarely used for other purposes in missiles.

Other Uses: When mixed with powdered metals, perchlorates, chlorates, or chromates have commercial use in flares and incendiary devices.

Appearance (as manufactured): The color of these materials varies with the oxidizer and fuel used. Numerous combinations exist, but the most likely (AP and aluminum powder) are light gray materials with a very fine texture.

Appearance (as packaged): Perchlorates, chlorates, or chromates, when mixed with powdered metals, are extreme fire or explosive hazards and are very unlikely to be shipped in such mixtures. Rather, they are shipped separately from powdered metals or other high-energy fuel components and then mixed together prior to casting into a motor stage

4.C.4. Oxidiser Substances as follows:
a. Oxidiser sustances usable in liquid propellant rocket engines as follows:
1. Dinitrogen trioxide (CAS 10544-73-7);
2. Nitrogen dioxide (CAS 10102-44-0) /dinitrogen tetroxide (CAS 10544-72-6);
3. Dinitrogen pentoxide (CAS 10102-03-1);
4. Mixed Oxides of Nitrogen (MON);
5. Inhibited Red Fuming Nitric Acid (IRFNA) (CAS 8007-58-7) ;
6. Compounds composed of fluorine and one or more of other halogens, oxygen or nitrogen;

Note:
Item 4.C.4.a.6. does not control Nitrogen Trifluoride (NF_3) (CAS 7783-54-2) in a gaseous state as it is not usable for missile applications.

Technical Note:
Mixed Oxides of Nitrogen (MON) are solutions of Nitric Oxide (NO) in Dinitrogen Tetroxide/Nitrogen Dioxide (N_2O_4/NO_2) that can be used in missile systems. There are a range of compositions that can be denoted as MONi or MONij where i and j are integers representing the percentage of Nitric Oxide in the mixture (e.g. MON3 contains 3% Nitric Oxide, MON25 25% Nitric Oxide. An upper limit is MON40, 40% by weight.)

Nature and Purpose: Oxidizers provide oxygen or halogen to burn the fuel in any rocket motor or engine. By carrying the fuel and oxidizer together, a missile is not dependent on the atmosphere for oxygen and can thus operate in space. Moreover, the oxidizer flow to a missile engine tends to be much greater than the rate of atmospheric oxygen capture that could be accomplished by an air inlet.

Method of Operation: In liquid propellant rocket engines, the oxidizer and fuel are fed from separate tanks then injected into the combustion chamber at great pressure, mixed, and ignited. In either case, heat causes atoms of oxygen or halogen to disassociate from the supplied oxidizer molecules and become more available to burn the fuel. Some liquid propellants are hypergolic, which means they react spontaneously on contact. Resulting hot gases accelerate through a rocket nozzle to produce thrust.

The oxidizer substances listed under MTCR Item 4.C.4.a. are very reactive, and hypergolic with the fuels with which they are usually paired (typically hydrazine and related fuels). Hypergolic combustion enables rocket engines be turned on and off very reliably by simply controlling valves, with no need for a separate ignition source inside the combustion chamber. The absence of a separate igniter permits hypergolic liquid rocket engines to be made very small as well as large, and there is no particular limit to the number of restarts. Repeated precision maneuvering is therefore possible. Another characteristic of commonly used hypergolic propellants is that they are typically liquids at ambient temperatures, unlike liquid oxygen, for example. As a result of the relative convenience, these propellants have been referred to as "earth storable propellants," or simply "storables." A significant disadvantage of hypergolic storables is that they

are extremely toxic to humans, and they react with or degrade most materials normally used for propellant storage containers.

- Brazil
- China
- France
- Japan
- Russian Federation
- United Kingdom
- United States
- Worldwide (for Nitric Acids)

- Only Russian Federation, Sweden, and the United States have produced ADN.

Global production



Typical Missile-Related Uses:

Dinitrogen trioxide (N_2O_3) is a black liquid at normal atmospheric pressure that decomposes above 3.5 °C and freezes at –102 °C. N_2O_3 is not often used as a missile propellant.

Dinitrogen tetroxide (N_2O_4), also known as nitrogen tetroxide (NTO), is a dimer of two molecules of nitrogen dioxide (NO_2) gas. NO_2 and N_2O_4 form an equilibrium, with greater disassociation to NO_2 at elevated temperatures and reduced pressures. While the two molecules coexist, the liquid is usually just referred to as N_2O_4 or NTO. N_2O_4 is a liquid at normal atmospheric pressure and temperature (from minus 11 °C to plus 21 °C). This narrow temperature range makes NTO impractical in systems that need to be stored full of propellant, such as mobile and tactical missiles. However, it has been successfully used for space launch vehicles (SLVs) that are filled shortly before launch, and also for missiles kept in temperature controlled environments such as silos (the U.S. Titan was both a silo-based missile and a SLV).

In order to reduce the freezing temperature of NTO, nitric oxide (NO) is often mixed in. The result is referred to as mixed oxides of nitrogen (MON), represented by MON-i, where i is a number for the percent of NO. While MON-3 is commonly used, rocket engines have been operated with MON-1, MON-10, MON-15, and MON-25. These propellants are green liquids with high vapor pressures and lower freezing temperatures that may permit an end-use in tactical missiles.

Dinitrogen pentoxide (N_2O_5) is not normally used as an oxidizer in liquid rocket engines because it is a solid at normal atmospheric pressure and temperature.

Inhibited Red Fuming Nitric Acid (IRFNA) has a high density and a low freezing-point; it is a commonly available nitric acid oxidizer favored for tactical missiles and some ballistic missiles. Nitric acid (HNO_3) is most widely sold as a concentrated solution in water, e.g. 70% nitric acid (not a propellant). Water can be eliminated in favor of NO_2, in which case the result is called red fuming nitric acid (RNFA) because some of the NO_2 readily enters the vapor phase as a reddish-brown gas. Additional substances are added to inhibit RFNA from corroding propellant tanks and other metal parts, hence IRFNA, sometimes referred to for clarity as “corrosion inhibited red fuming nitric acid.”

Chlorine trifluoride (ClF_3) and *chloryl (per-)fluoride* (ClO_3F) are the two most common halogen-based oxidizers. Because they are very toxic and energetic oxidizers, they are difficult to handle. Thus, they are rarely used except for technology development. Other inter-halogen oxidizers have been developed and

tested but they are not used because of cost, handling, and safety considerations. For example, chlorine pentafluoride (ClF_5) and fluorox (ClF_3O) are difficult to make safely and are not readily available. They were originally developed because fluorine/hydrazine is a very high performing propellant combination, but the fluorine must be kept below its boiling point (–188 °C) to keep it from boiling off and is thus impractical for use as an oxidizer for tactical missiles. The same is true for chlorine. Halogen-based oxidizers are unlikely to be encountered in fielded missiles around the world.

Other Uses: N_2O_4 and MON-3 are commonly used in satellites, science spacecraft, and in orbital maneuvering systems, typically with electric resistance heaters on tank walls to prevent freezing. Nitrogen dioxide (NO_2) and N_2O_4 is the precursor for all nitric acid production and is used as a nitrating agent for agricultural chemicals, plastics, paper, and rubber. N_2O_5 is used to make explosives and is a nitrating agent in organic chemistry.

Concentrated nitric acid, the main constituent of IRFNA, is used to make pharmaceuticals and explosives.

Chlorine and fluorine have many commercial uses. Chlorine is used widely to purify water, to disinfect or bleach materials, and to manufacture many important compounds including chloroform and carbon tetrachloride. ClF_3 is used in nuclear fuel reprocessing, semiconductor manufacturing, and ClO_3F is used as a gaseous dielectric in transformers.

Appearance (as manufactured) (Measurements are at standard temperature and pressure): NO_2 is a red-brown gas, and N_2O_4 at typical ambient temperatures is a red-brown liquid due to its equilibrium NO_2 content. Depending on temperature and pressure, NO_2 and N_2O_4 form equilibria at various percentages. The density of N_2O_4 is 1.43 g/ml, and it freezes at –11 °C and boils at +21 °C.

Mixed oxides of nitrogen (MON) liquids appear green in color due to the addition of nitric oxide (NO) into the equilibrium of NO_2 and N_2O_4. Their freezing points are lower than for N_2O_4. The green appearance is typically only seen through glassware, because the reddish-brown color of NO_2 vapor dominates the appearance when evaporation is permitted (e.g. from a vessel open to the atmosphere).

Red-fuming nitric acid (RFNA) is nearly anhydrous nitric acid that is stabilized with high concentrations of added nitrogen dioxide. Roughly 15% NO_2 is typically dissolved in the acid but more can be added to increase the liquid density. Maximum density nitric acid (MDNA) is 56% HNO_3 and 44% N_2O_4. Because nitric acid is corrosive to most non-noble materials (materials that react chemically), a small amount (approximately 0.75%) of hydrofluoric acid (HF) is added as a corrosion inhibitor to produce IRFNA. When IRFNA is stored in stainless steel or aluminum containers, the HF forms protective fluorides that reduce the rates of wall corrosion. IRFNA freezes at approximately –65 °C and boils at approximately +60 °C. Its density at normal room temperature is about 1.55 g/ml, depending on the amount of N_2O_4 added.

Fluorine is a pale yellow, highly corrosive, poisonous, gaseous, halogen element. It is usually considered the most reactive of all the elements. Its freezing point is –220 °C, and its boiling point is –188 °C, which makes it a cryogenic liquid. Its specific gravity in the liquid state is 1.108 g/ml at its boiling point.

Chlorine is a greenish-yellow gas that is highly irritating and capable of combining with nearly all other

elements. It is produced mainly by electrolysis of sodium chloride. Its freezing point is –101 °C; its boiling point is –35 °C; and its specific gravity is 1.56 g/ml (at –34 °C).

Chlorine pentafluoride (ClF_5), which boils at –14 °C at one atmosphere pressure, must be pressurized to maintain liquid form at typical ambient temperatures. It has a high density of 1.78 g/ml at +25 °C. Because chlorine trifluoride (ClF_3) boils at +12 °C, it is easier to handle than ClF_5 but it must still be pressurized for shipping. Bromine pentafluoride (BrF_5) boils at +40 °C, but other characteristics such as shock sensitivity, toxicity, corrosiveness, and lower specific impulse potential make it an impractical propellant.

Nitrogen trifluoride (NF_3) is a cryogenic oxidizer that boils at –130 °C and has a density of 1.55 g/ml at its normal boiling point. Nitrogen tetrafluoride (N_2F_4) has a higher density and boiling point but is also cryogenic.

Appearance (as packaged): Nitric acid, NTO, and MON are usually stored in stainless steel tanks that have been specially prepared. Aluminum tanks and lines can also be compatible. Packages for shipping these chemicals use identifying words, warnings, labels, and symbols. NTO and MON must be shipped in containers that hold pressure, due to the high vapor pressures associated with relatively low boiling points.

IRFNA is usually stored and shipped in aluminum tanks that have been specially prepared. Stainless steel tanks and lines are also compatible.

If properly labeled, containers should specify "oxidizer" and have numerical information such as United Nations designations for international hazardous shipments. Examples of the latter numbers are UN 1067 and UN 2032, respectively, for NTO or MON, and for RFNA or IRFNA. There is also a system of CAS numbers, e.g. 10102-44-0 refers to both NO_2 and N_2O_4.

Exotic propellants such as chlorine and fluorine are cryogenic liquids and are extremely reactive and toxic. Accordingly, their shipping and handling are tightly regulated. Ordinary metal containers cannot be used to contain them. Super-cooled and pressurized tanks are required to ship in liquid form. Oxygen difluoride (OF_2) can be stored at low temperatures in glass-lined, stainless steel tanks that have been specially prepared.

4.C.4.b. Oxidiser Substance usable in solid propellant rocket motors as follows:
1. Ammonium perchlorate (AP) (CAS 7790-98-9);
2. Ammonium dinitramide (ADN) (CAS 140456-78-6);
3. Nitro-amines (cyclotetramethylene-tetranitramine (HMX) (CAS 2691-41-0); cyclotetrimethylene-trinitramine (RDX) (CAS 121-82-4);
4. Hydrazinium nitroformate (HNF) (CAS 20773-28-8);
5. 2,4,6,8,10,12-Hexanitrohexaazaisowurtzitane (CL-20) (CAS 135285-90-4).

- Belgium
- China
- Denmark
- France
- Finland
- Germany
- India
- Netherlands
- Norway
- Russian Federation
- Spain
- Switzerland
- Ukraine
- United Arab Emirates
- United Kingdom
- United States

- **HNF**
- Netherlands
- United States

Global production



Nature and Purpose: Solid oxidizers provide oxygen needed to burn solid rocket motor fuel. By carrying fuel and oxidizer together, the rocket does not depend on the atmosphere for oxygen. Nitro-amines are not oxidizers per se; they are high explosives added to propellants to increase their performance.

Method of Operation: The solid oxidizer is mixed evenly with fuels and cast into a rocket motor. The oxygen disassociates during the burn process and becomes available to rapidly burn available fuel and, by generating gases exhausted at very high speeds, produce thrust.

Typical Missile-Related Uses: AP is an oxidizing agent used by most modern solid propellant formulas. Depending on the formulation, it accounts for 50% to 85% of the propellant by weight.

ADN is an oxidizing agent for solid propellant. This material is used in a manner similar to AP.

HMX, sometimes called Octogen, and RDX, sometimes called Cyclonite, are high-energy explosives often added to solid propellants to lower the combustion temperature and reduce smoke. Usually less than 30% of the propellant weight is HMX or RDX.

HNF is an energetic oxidizer used for solid rocket propellants; its combustion is very efficient and when combined with modern binders, has a very small ecological impact as it is free of chlorines. 2,4,6,8,10,12-Hexanitrohexaazaisowurtzitane is about 20% more powerful than HMX.

Other Uses: AP is used in explosives, pyrotechnics, and analytical chemistry, and as an etching and engraving agent. ADN has no known commercial uses. HMX and RDX are used in warheads, military and civilian explosives, and oil well pipe cutters. HNF has no known commercial uses outside aerospace/rocket propellant.

Appearance (as manufactured): AP is a white or, depending on purity, off-white crystalline solid, similar in appearance to common table salt. ADN is a white, waxy, crystalline solid that may appear as thin platelets or small round pills. HMX and RDX are white crystalline materials that resemble very fine table salt. HNF is a yellow crystalline material that resembles long needles, although further development has produced a granular form. 2,4,6,8,10,12-Hexanitrohexaazaisowurtzitane are crystalline materials.

Appearance (as packaged): AP is usually packaged and shipped in 30- or 55-gallon polyethylene-lined drums with oxidizer or explosive symbol markings. Two different types of AP containers and their markings are shown in Figure 58. ADN is packaged and shipped in a similar manner to AP. HMX and RDX are usually packaged and shipped either in water or alcohol (because in dry form they are prone to explode) in 30- or 55-gallon polyethylene-lined drums with oxidizer or explosive symbol markings.

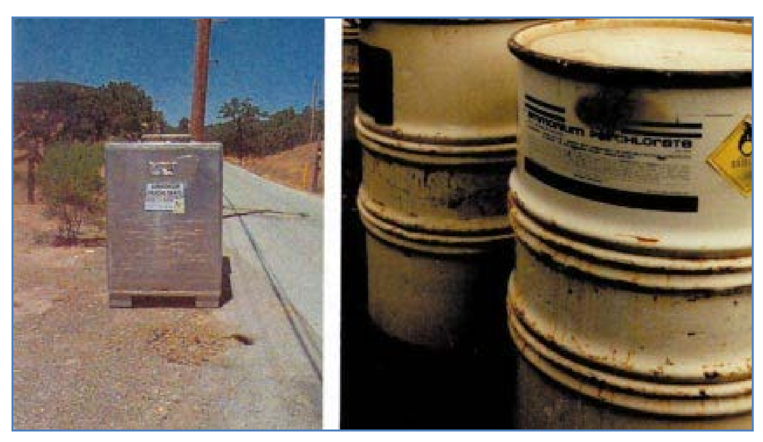


Figure 58: Two different ammonium perchlorate shipping containers. (The Charles Stark Draper Laboratories & Kerr McGee)

Additional Information: AP is generally produced with an average particle size of 200 to 400 microns (70 to 40 mesh). The density of AP is 1.95 g/cc, but the bulk density is less and varies with particle size. AP decomposes violently before it melts. The chemical formula of AP is NH_4ClO_4. ADN has a density of 1.75 g/cc and a reported melting point of 92-95 °C. The chemical formula for ADN is $NH_4N(NO_2)_2$.

HMX and RDX are generally produced with a particle size of 150 to 160 microns (100-80 mesh). HMX has a density of 1.91 g/cc, a melting point of 275 °C, and a chemical formula of $C_4H_8N_8O_8$. RDX has a density of 1.81 g/cc, a melting point of 204 °C, and a chemical formula of $C_3H_6N_6O_6$. HMX and RDX also decompose violently at their melting points.

4.C.5. Polymeric Substances, as follows:
a. Carboxy-terminated polybutadiene (including carboxyl-terminated polybutadiene) (CTPB);
b. Hydroxy-terminated polybutadiene (including hydroxyl-terminated polybutadiene) (HTPB) *(CAS 69102-90-5)*;
c. Glycidyl azide polymer (GAP), including hydroxyl-terminated GAP;
d. Polybutadiene-Acrylic Acid (PBAA);
e. Polybutadiene-Acrylic Acid-Acrylonitrile (PBAN) *(CAS 25265-19-4 / CAS 68891-50-9)*;
f. Polytetrahydrofuran polyethylene glycol (TPEG).

Technical Note:
Polytetrahydrofuran polyethylene glycol (TPEG) is a block co-polymer of poly 1,4-Butanediol and polyethylene glycol (PEG) (CAS 25322-68-3).

- China
- France
- India
- Japan
- Russian Federation
- United States

Global production



Nature and Purpose: These six polymers are chemicals used as a binder and fuel in solid rocket motor propellant. They are liquids that polymerize during motor manufacture to form the elastic matrix that holds the solid propellant ingredients together in a rubber-like polymeric composite material. They also burn as fuels and contribute to overall thrust. GAP is the only energetic polymer in this group. It provides energy as a result of its decomposition during the combustion process.

Method of Operation: Batch mixers (or, rarely, continuous mixers for very large scale production) are used to blend carefully controlled ratios of rocket motor propellant ingredients into the polymeric substance. The viscous, well blended material is then cast into a rocket motor case, in which it polymerizes and adheres to either an interior liner or insulator inside the rocket motor case. The result is a rocket motor fully loaded with solid propellant.

Typical Missile-Related Uses: These polymeric substances are used in the production of solid propellant for solid rocket motors and hybrid rocket motors. They are also used in the production of smaller solid rocket motors used to launch cruise missiles and other UAVs. These binding ingredients greatly affect motor performance, aging, storability, propellant processing, and reliability.

Although all these materials are of concern as potential solid propellant binders, HTPB is the preferred binder. At present, no fielded ballistic missile systems use GAP or PBAA. CTPB and PBAN have largely supplanted PBAA because of their superior mechanical and aging characteristics.

Other Uses: PBAN has no commercial uses. HTPB has extensive uses in asphalt and electronics, and as a sealant.

Appearance (as manufactured): These six polymeric materials are clear, colorless, viscous liquids. Antioxidants are added at the level of one percent or less at the time of manufacture in order to improve shelf life; they impart a color to the materials that may range from light yellow to dark brown. This color depends on the type and amount of antioxidant used.

The viscosity of these six liquids ranges from that of light syrup to that of heavy molasses. Except for GAP, which is nearly odorless and has a specific density of 1.3 g/cc, the polybutadiene-based polymers have a distinctive petroleum-like odor and densities slightly less than that of water (0.91 g/cc to 0.94 g/cc).



Figure 59: A Polybutadiene-Acrylic Acid-Acrylonitrile (PBAN) shipping drum. (The Charles Stark Draper Laboratories)

Appearance (as packaged): These liquids are usually shipped in 55-gallon steel drums. The interiors of the drums are usually coated with an epoxy paint or other material to prevent rusting. If the liquids are shipped in stainless steel drums, the coating is not necessary. Smaller or larger containers may be used depending on the quantity being shipped; tank-cars or tank- trucks may be used to ship very large quantities. An example of PBAN in its shipping drum is presented in Figure 59.

4.C.6. Other propellant additives and agents as follows:

a. Bonding agents as follows:

1. Tris (1-(2-methyl) aziridinyl) phosphine oxide (MAPO) (CAS 57-39-6);
2. 1,1',1" -trimesoyl-tris (2-ethylaziridine) (HX-868, BITA) (CAS 7722-73-8);
3. Tepanol (HX-878), reaction product of tetraethylenepentamine, acrylonitrile and glycidol (CAS 68412-46-4);
4. Tepan (HX-879), reaction product of tetraethylenepentamine and acrylonitrile (CAS 68412-45-3);
5. Polyfunctional aziridine amides with isophthalic, trimesic, isocyanuric, or trimethyladipic backbone also having a 2-methyl or 2-ethylaziridine group;

Note:

Item 4.C.6.a.5 includes:

1. 1,1' -Isophthaloyl-bis (2-methylaziridine) (HX-752) (CAS 7652-64-4);
2. 2,4,6-tris (2-ethyl-1-aziridinyl)- 1,3,5-triazine (HX-874) (CAS 18924-91-9);
3. 1,1' -trimethyladipoylbis (2-ethylaziridine) (HX-877) (CAS 71463-62-2).

Nature and Purpose: Propellant bonding agents are used to improve the bond or adhesion between the binder and the oxidizer, typically AP. This process vastly improves the physical properties of the propellant by increasing its capability to withstand stress and strain. Bonding agents are normally used only with HTPB propellants. Some bonding agents are used as curing agents or cross-linkers with CTPB or PBAN propellants.

- **MAPO**
- France
- India
- Japan
- Russian Federation
- United States
- **BITA, Tepanol and Tepan, PAAs**
- United States
- The United States is the main producer and supplier of these materials, but some European and Asian countries may have production licenses, and production of these materials may be more widespread because the composition of these materials is open-source information and production methods are not difficult to duplicate.

Global production



Method of Operation: Bonding agents are added to the propellant during the mixing operation at levels usually less than 0.3%. The bonding agent reacts with the AP to produce a very thin polymeric coating on the surface of the AP particle. This polymeric coating acts as an adhesive between the AP and the HTPB binder. The molecular structure stays much the same.

Typical Missile-Related Uses: Propellant bonding agents are used to polymerize propellants (bond the oxidizer) for solid rocket motors. MAPO is a curing agent for CTPB prepolymers and a bonding agent for HTPB prepolymers. BITA is a bonding agent with HTPB. Tepan is a bonding agent with HTPB. Polyfunctional aziridene amides (PAAs) are bonding agents with HTPB and thickeners for CTPB and PBAN.

Other Uses: MAPO is used only in solid rocket propellants. BITA is used with HTPB in the commercial sector, especially in electronics, as a sealant and a curing agent for CTPB prepolymers. Tepanol and Tepan are used only in solid rocket propellants. PAAs are used in adhesives in the commercial sector.

Appearance (as manufactured): MAPO is a slightly viscous amber liquid. It has a very distinctive acrid odor. It polymerizes violently if it comes into contact with acids and AP. Its boiling point is 1,200 °C at 0.004 bar; its density is 1.08 g/cc and its chemical formula is $C_9H_{18}N_3OP$. BITA is a light yellow, viscous liquid; when cooled below 160 °C, BITA is a pale, off-white, waxy solid. BITA has no sharply defined melting point, a density of 1.00 g/cc, and a chemical formula of $C_{21}H_{27}N_3O_3$. Tepanol is a dark yellow, viscous liquid. It has a very strong odor like that of ammonia. Tepan is much less viscous than Tepanol but identical to it in all other respects including a very strong odor like that of ammonia. PAAs are similar to BITA.

Appearance (as packaged): MAPO is packaged and shipped in standard, 1- to 55-gallon steel cans or drums. BITA, Tepanol, Tepan, and PAA are packaged in 1-gallon steel cans that are usually shipped in insulated containers packed with dry ice and stored at 0 °C or less in order to maintain its useful shelf life.

4.C.6.b. Curing reaction catalysts as follows:
Triphenyl bismuth (TPB) (CAS 603-33-8)

- France
- Japan
- Switzerland
- United States

Global production



Nature and Purpose: Curing agents and catalysts are used to polymerize solid rocket motors; that is, they cause the viscous mixture of liquid polymeric substance and other solid propellant ingredients to solidify into a rubbery composite that adheres to the inner lining or insulator inside the motor case.

Method of Operation: TPB is added in small quantities to HTPB to trigger a relatively mild chemical reaction known as polymerization. The molecular structure of HTPB stays much the same but the material converts from liquid to solid form due to molecular cross-linking.

Typical Missile-Related Uses: TPB is used as a cure catalyst in HTPB solid rocket propellants.

Other Uses: TPB is used in some plastics.

Appearance (as manufactured): TPB is a white to light tan crystalline powder. TPB has a density of 1.7 g/cc, a melting point of 78 °C, and the chemical formula $C_{18}H_{15}Bi$.

Appearance (as packaged): TPB is packed in brown glass containers because of its sensitivity to light. These containers range in capacity from a few grams to 5 kg. When shipped in larger quantities, TPB may be packed in polyethylene bags inside fiber packs or cardboard cartons.

4.C.6.c. Burning rate modifiers as follows:
1. Carboranes, decaboranes, pentaboranes and derivatives thereof;
2. Ferrocene derivatives, as follows:
   a. Catocene (CAS 37206-42-1);
   b. Ethyl ferrocene (CAS 1273-89-8);
   c. n-Propyl ferrocene (CAS 1273-92-3) / iso-propyl ferrocene (CAS 12126-81-7);
   d. n-Butyl-ferrocene (CAS 31904-29-7);
   e. Pentyl ferrocene (CAS 1274-00-6);
   f. Dicyclopentyl ferrocene (CAS 125861-17-8);
   g. Dicyclohexyl ferrocene;
   h. Diethyl ferrocene (CAS 1273-97-8);
   i. Dipropyl ferrocene;
   j. Dibutyl ferrocene (CAS 1274-08-4);
   k. Dihexyl ferrocene (CAS 93894-59-8);
   l. Acetyl ferrocene (CAS 1271-55-2) / 1.1'-diacetyl ferrocene (CAS 1273-94-5);
   m. Ferrocene Carboxylic acid (CAS 1271-42-7) / 1,1'-Ferrocenedicarboxylic acid (CAS 1293-87-4);
   n. Butacene (CAS 125856-62-4);
   o. Other ferrocene derivatives usable as rocket propellant burning rate modifiers;

Note:
Item 4.C.6.c.2.0. does not control ferrocene derivatives that contain a six carbon aromatic functional group attached to the ferrocene molecule.

Nature and Purpose: Burning rate modifiers are chemical additives to solid rocket propellant that alter the rate at which the fuel burns. The purpose is to tailor the rocket motor burn time to meet requirements.

Method of Operation: Burning rate modifiers are blended in carefully controlled quantities into rocket motor propellant during production.

Typical Missile-Related Uses: They are added to propellant to modify burn rates and allow designers to tailor the thrust profile to meet requirements.

Other Uses: Some borane derivatives have commercial uses as catalysts in olefin polymerization, water treatment, used in the pharmaceutical industry for disease diagnosis treatment, and as agents in rubber vulcanization.

Appearance (as manufactured): Catocene is a slightly viscous, dark red liquid but appears yellow in a thin film or as a yellow stain on white cloth or paper. It is a mixture of six isomers, all with high boiling temperatures. It is insoluble in water but soluble in most organic solvents. It has a density of 1.145 g/cc, slightly greater than that of water. Catocene has the chemical formula $C_{27}H_{32}Fe_2$. Catocene, the commercial trade name for 2,2'-bis (ethylferrocenyl) propane, is probably the most widely used ferrocene in the propellant industry. All ferrocene derivatives contain iron and are added to propellants containing

- **For Catocene**
  - United States
- **For Ferrocene derivatives**
  - China
  - France
  - Germany
  - Japan
  - Russian Federation
  - Switzerland
  - United Kingdom
  - United States
- **For Borane derivatives**
  - France
  - Russian Federation
  - United Kingdom
  - United States
- **For Butacene**
  - France

Global production



AP.

Ferrocene and its derivates are orange to yellow crystal powders. They are organometallic compounds with a sandwich structure.

N-butyl ferrocene and other ferrocene derivatives are similar in appearance to Catocene. Ferrocenes have fewer applications in Category I missiles than in smaller tactical missiles. They increase propellant sensitivity to accidental ignition by friction and electrostatic discharge.

Butacene is unique as it is both an HTPB binder and a burn rate modifier. It is a very high-viscosity liquid that resembles a very heavy, dark corn syrup or molasses.

Carboranes, decarboranes, pentaboranes, and their derivatives are clear, colorless liquids with no distinct odor. The most common carborane derivatives used in solid propellants are n-hexyl carborane and carboranylmethyl propionate. Carboranes may cause nerve damage, according to a few studies. Alkali metal salts of decarboranes and pentaboranes are white powders. Most borane derivatives are less dense than water and are toxic. Borane derivatives are used to produce extremely high burn rates in solid propellants. Borane derivatives are extremely expensive to produce. They are rarely used in ballistic missile propellants.

Appearance (as packaged): All of these materials are shipped in steel drum containers ranging in capacity from 1 gal to 55 gal.

4.C.6.d. Esters and plasticisers as follows:
1. Triethylene glycol dinitrate (TEGDN) (CAS 111-22-8);
2. Trimethylolethane trinitrate (TMETN) (CAS 3032-55-1);
3. 1,2,4-butanetriol trinitrate (BTTN) (CAS 6659-60-5);
4. Diethylene glycol dinitrate (DEGDN) (CAS 693-21-0);
5. 4,5 diazidomethyl -2-methyl-1,2,3-triazole (iso-DAMTR);
6. Nitratoethylnitramine (NENA) based plasticisers, as follows:
    a. Methyl-NENA (CAS 17096-47-8);
    b. Ethyl-NENA (CAS 85068-73-1);
    c. Butyl-NENA (CAS 82486-82-6);
7. Dinitropropyl based plasticisers, as follows:
    a. Bis (2,2-dinitropropyl) acetal (BDNPA) (CAS 5108-69-0);
    b. Bis (2,2-dinitropropyl) formal (BDNPF) (CAS 5917-61-3);

- Any country can acquire the capability to produce these products. Any country that has set up a nitration plant, such as for the production of explosives, could produce a variety of these nitrate esters.

Global production



Nature and Purpose: These nitrate esters, also known as nitrated plasticizers, are additives to solid rocket propellants used to increase their burn rate.

Method of Operation: Nitrate esters and nitrated plasticizers are liquid explosives that contain enough oxygen to support their own combustion. They are generally added to high performance propellants containing HMX and aluminum to achieve higher performance.

Typical Missile-Related Uses: Nitrate esters and nitrated plasticizers are added to double-base propellants to increase their propulsive energy. Because plasticizers do not react with the cure agents and remain liquid at low temperatures, they make solid propellants less likely to crack or shrink in cold temperatures.

Other Uses: Nitrate esters are used as components of military and commercial explosives.

Appearance (as manufactured): Nitrate esters are dense, oily liquids ranging in color from clear to slightly yellow.

Appearance (as packaged): Nitrate esters are shipped in 5 to 55 gallon steel drums marked with labels indicating explosives. Except for BTTN, these nitrate esters are shipped undiluted unless the end-user requests that they be shipped diluted with a solvent. Because of its sensitivity to shock, BTTN is shipped diluted with either methylene chloride or acetone. When diluted with methylene chloride, BTTN has a sweet odor like that of chloroform. When diluted with acetone, it has an odor like that of nail polish. When stabilizers are added (usually at the 1.0% level) the nitrate ester acquires a deep red color.

4.C.6.e. Stabilisers as follows:
1. 2-Nitrodiphenylamine (CAS 119-75-5);
2. N-methyl-p-nitroaniline (CAS 100-15-2).

- **2-NDPA**
  - France
  - Japan
  - Switzerland
  - United Kingdom
  - United States
- **MNA**
  - Switzerland
  - United Kingdom
  - United States

Global production



Nature and Purpose: 2-nitrodiphenylamine (2-NDPA) and N-methyl-p-nitroaniline (MNA) are additives that inhibit or reduce decomposition of rocket fuels containing nitrate esters or nitrocellulose. These types of propellants are referred to as double-base, composite-modified double-base, or cross-linked double-base propellants.

Method of Operation: These stabilizers alter the chemical environment within the propellant to reduce decomposition of its constituents.

Typical Missile-Related Uses: These stabilizers make composite propellants less subject to the effects of aging. As a result, they increase the effective lifetime of solid propellant missiles.

Other Uses: 2-NDPA is used in explosives as a nitroglycerin stabilizer. It is used widely throughout the ammunition industry. MNA has no known commercial uses.

Appearance (as manufactured): In its pure state, 2-NDPA is a bright yellow, crystalline solid with a density of 1.15 g/cc and a melting point of 74-76 °C. The chemical formula for 2-NDPA is $C_{12}H_{10}N_2O_2$. When exposed to light, 2-NDPA turns to a dark orange color.

MNA is also a bright yellow, crystalline solid with a density of 1.20 g/cc and a melting point of 152–154 °C. The chemical formula for MNA is $C_7H_8N_2O_2$.

Appearance (as packaged): When shipped in small quantities, 2-NDPA and MNA are packaged in brown glass containers because they are sensitive to light. When shipped in larger quantities, they are packaged in polyethylene bags and placed inside fiberpack or cardboard containers.

4.C.7 'Gel propellants' specifically formulated for use in the systems specified in 1.A., 19.A.1. or 19.A.2.

Technical Note:

A 'gel propellant' is a fuel or oxidiser formulation using a gellant such as silicates, kaolin (clay), carbon or any polymeric gellant.

N.B. CAS numbers included in Item 4.C. are Technical Notes. For the use of CAS numbers in the Annex, see Introduction Section (f).

- China
- Germany
- United States

Global production



Nature and Purpose: Gel propellant behaves like a solid propellant in storage and like a liquid propellant in use. Gel propellant combines the easier handling and long storage time of solid rocket propellant with the ability to throttle, control thrust, and restart a liquid rocket engine. Gel propellant provides a better specific impulse than either solid or liquid propellants.

Method of Operation: The pressurized stage of a gel propellant rocket provides the needed pressure to force the gel propellant into the combustion chamber. The upper stage will contain some method of delivering a high-pressure gas, either helium or the use of a solid propellant gas generator, to push the gel propellant into the combustion chamber. If a solid propellant gas generator is used to generate the pressure the tank will require some form of a heat shield.

Typical Missile-Related Uses: Gel propellants are used to reduce gross lift off weight due to having a lower density than liquid or solid fuel. Gel propellants provide a high degree of sensitivity while producing minimum smoke, thus a low signature. Gel-based rocket propellant could provide the best combination – permitting modulation of thrust as in liquid propellant engines to maximize weapon endurance and performance, while offering the extended shelf life and high operational readiness of solid rocket motors.

Other Uses: N/A.

Appearance (as manufactured): Gel propellants are clear-gelled liquids with a firm consistency ranging in color from clear to yellow.

Appearance (as packaged): N/A.

4.D. Software

4.D.1. "Software" specially designed or modified for the operation or maintenance of equipment specified in 4.B. for the "production" and handling of materials specified in 4.C.

- Argentina
- Austria
- Brazil
- Canada
- Czech Republic
- Finland
- Germany
- India
- Israel
- Japan
- Netherlands
- North Korea
- Poland
- Slovak Republic
- Republic of Korea
- Sweden
- Syria
- United Kingdom
- Australia
- Belgium
- Bulgaria
- China
- Egypt
- France
- Greece
- Iran
- Italy
- Luxembourg
- New Zealand
- Pakistan
- Russian Federation
- South Africa
- Spain
- Switzerland
- Ukraine
- United States


Global production



Nature and Purpose: As stated in 4.B.1, the production equipment required to manufacture liquid propellant are common in the chemical and petroleum industries. The process-control software from those industries can be used in liquid propellant manufacturing facilities with modification to accommodate the unique properties of the propellants. Liquid propellants can be toxic, hazardous to handle and highly flammable or readily support combustion. Process control software specifically designed for producing these propellants reduce risk and result in consistent output.

Analytical equipment used in liquid propellant acceptance-testing laboratories is largely automated. This off-the-shelf test equipment produces reliable and accurate analyses with no modification to the operating software.

Solid propellant production facilities are primarily batch oriented operations Fluid energy mills are used to produce a specific particle size for the oxidizer. Metal powder production equipment is used to produce the fuel additives specified in 4.C.2.c, 4.C.2.d and 4.C.2.e. These systems may use specifically designed process control software to maintain the proper process parameters. Scales (analog or digital) are used to measure precise amounts of the propellant ingredients (fuel, oxidizer, binder, inhibitors, stabilizers, burn-rate modifiers and curing agents). Computer-controlled vacuum mixing systems are used to combine the propellant ingredients that results in a viscous slurry. Software controls the vacuum level, cooling and mixing times for the process. After the propellant is poured into the motor case, it must be cured at elevated temperature for a specific amount of time. These curing parameters are essential to allow the mechanical properties to stabilize and are often controlled by software operating the oven or curing room. Analytical equipment used to evaluate solid propellant also relies on automated equipment to determine

its chemical composition. Propellant samples are ignited and the properties of these samples are analyzed in bomb calorimeters and infrared spectrometers. Solid propellant samples are also evaluated for mechanical strength and ability to withstand stress and strain in computer-aided stress/strain test and measuring equipment. X-ray radiography is used to evaluate the propellant for voids and the propellant/liner bond integrity. These systems feed the quality control software associated with propellant production.

Method of Operation: The software is loaded on computers as small as a PC or a PLC to control the specified process. Software used to control the electromechanical valves and other equipment found in a chemical plant can be used to manage fluid transfer, heat management and other processes used to manufacture liquid propellants. Software manages the process parameters for the solid propellant mixers, the metal powder production equipment and the curing stations. Numeric control machines are used to mill and machine the surfaces of solid propellant motor cores to remove waste left when the mandrel is removed from the motor. In advanced facilities all of the individual process controllers and computers are networked to a control center where overall operations are monitored.

Other Uses: Much of the software used in the production of liquid and solid propellants is commercially available and modified to support propellant production. Some of the software is process/machine specific with no other known use.

Appearance (as manufactured): Typically this software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives, and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use, unless the software is run on the appropriate computer. This technology, including the documentation, can be transmitted over a computer network.

4.E. Technology

4.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or materials specified in 4.B. and 4.C.

Nature and Purpose: Propellant technology is the knowledge required to develop or use the equipment specified in 4.B to produce or use the materials specified in 4.C for the production of liquid or solid propellant. This knowledge includes formulation and manufacturing of liquid or solid propellant constituents, mixing ratios of the propellant constituents, machine and process operating parameters, drawings, manuals and training. This knowledge is often considered proprietary to the specific equipment or process involved.

Method of Operation: The technology used to design liquid propellant production facilities can be gained from chemical engineering textbooks. Any industrial country with chemical or petroleum industries has the basic knowledge and expertise. It is the acquisition or transfer of knowledge to specially design, manufacture and use the elements required for liquid propellant production that is controlled.

The technology associated with solid propellant production is more specialized. The formulae and processing parameters for a particular solid propellant is likely country/manufacturer proprietary and controlled. Any modifications to fluid energy mills, powder metal production equipment or mixers to meet the requirements for producing the constituents and/or the final propellant are controlled.

A country seeking to develop an indigenous propellant production capability has several options. The country can buy the technology as a turn-key operation from a third party. The country may leverage existing knowledge in the case of chemical or petroleum industry experience and hire consultants with the expertise in modifying equipment for propellant production. A third option would be to send technical personnel to training in other countries to acquire the knowledge to stand up the process from scratch.

Typical Missile-Related Uses: This technology is used to produce propellants that power missiles.

Other Uses: N/A.

Appearance (as manufactured): N/A.

Appearance (as packaged): N/A.

Category II - Item 5

Reserved for Future Use

Category II - Item 6

Production of Structural Components, Pyrolytic Deposition and Densification, and Structural Materials

Category II – Item 6: Production of Structural Components, Pyrolytic Deposition and Densification, and Structural Materials

6.A. Equipment, Assemblies and Components

6.A.1. Composite structures, laminates, and manufactures thereof, specially designed for use in the systems specified in 1.A., 19.A.1. or 19.A.2. and the subsystems specified in 2.A. or 20.A.

- China
- France
- Israel
- Japan
- South Africa
- United Kingdom
- Denmark
- Germany
- India
- Russian Federation
- Sweden
- United States

Global Production



Nature and Purpose: Composites and laminates are used to make rocket and unmanned aerial vehicle (UAV) parts that are often lighter weight, stronger, and more durable than parts made of metals or other materials.

Typical Missile-Related Uses: Composites and laminates are generally used in critical structural components of ballistic missiles or UAVs, including cruise missiles. Uses include solid rocket motor cases, interstages, wings, inlets, nozzles, heat shields, nosetips, structural members, and frames.

Other Uses: Composite structures can be formed into almost any shape to meet required needs. They can increase the speed of product manufacturing, and allow greater flexibility in the configuration of the final product. Composites can be manufactured to provide directional strength where required while reducing weight compared to their metal counterparts. They are used both in civilian and military aircraft, as armor for military vehicles, in recreational products (skis, tennis racquets, boats, and golf clubs), automotive parts, laptops, smart phones and in infrastructure (bridge repairs and as concrete reinforcement).

Appearance (as manufactured): Composites assume the shape of the object, mandrel or mold on which they are formed. The reinforcement used to make a composite often results in a textile-like pattern on the surface of the object, especially when pre-impregnated cloth is used. Even when cloth is not used, the linear pattern of the tape may still be present. Paints and gel coatings sometimes may conceal this pattern.

Appearance (as packaged): Composite structures are packaged much like other structures, with foam or other materials to protect them from surface abrasions or distortions from stress.

6.A.2. Resaturated pyrolised (i.e. carbon-carbon) components having all of the following:
a. Designed for rocket systems; and
b. Usable in the systems specified in 1.A. or 19.A.1.

- France
- India
- Japan
- Russian Federation
- United Kingdom
- United States

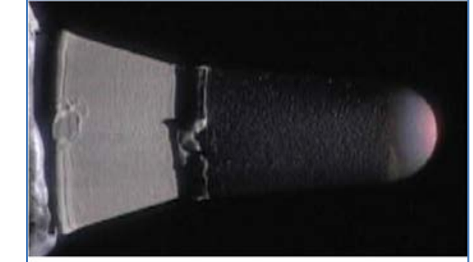
Global Production



Nature and Purpose: Carbon-carbon is a composite of carbon fiber, usually made from pitch, rayon, or polyacrylonitrile (PAN), in a carbon (or graphite)-dominated matrix. It is usually made by using a high-content carbon resin as the initial matrix and then driving off the non-carbon elements through high heat. It is lightweight, highly heat-resistant, thermal-shock-resistant, and malleable for shaping.

Typical Missile-Related Uses: Carbon-carbon materials are used for items such as rocket motor exit cones and nozzles, and Re-entry Vehicle (RV) nosetips, heat shields, and leading edges of control surfaces that must resist the effects of high temperatures and ablation. Figure 60 shows the results of a 300-second arc jet test on a carbon-carbon nose cone coated with layered silicon-carbide. No mass or dimensional changes in the structure of the cone were evident after exposure to extremely high temperatures.

Other Uses: Carbon-carbon structures are used in military and civilian aircraft applications such as high-temperature brake shoes, and in other applications requiring high strength and low weight such as wing roots. They can also be used for tooling requiring long life in severe, usually high-temperature manufacturing environments, such as pouring ladles for steel, heaters for high-temperature furnaces, hot glass handling tools and hot press tools.



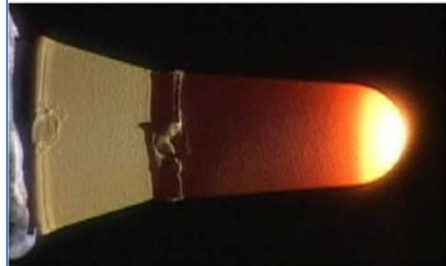


Figure 60: The effects of high temperatures on a carbon-carbon nose cone are seen after 15 seconds (upper image) and 295 seconds. (Ultramet Advanced Materials Solutions)

Appearance (as manufactured): Typical carbon-carbon materials designed for rocket systems are black and have a patterned surface as a result of textile reinforcement. Nosetips and rocket nozzles are usually machined from blocks or billets or can be woven to shape.

Appearance (as packaged): Before machining, blocks of carbon-carbon material are rugged enough to be packed in filler and shipped in cardboard boxes. Machined parts require careful packaging because, although resistant to breaking (impact resistant), they can easily be gouged or scraped.

6.B. Test and Production Equipment

6.B.1. Equipment for the "production" of structural composites, fibres, prepregs or preforms, usable in the systems specified in 1.A., 19.A.1. or 19.A.2., as follows, and specially designed components, and accessories therefor:
a. Filament winding machines or 'fibre/tow-placement machines', of which the motions for positioning, wrapping and winding fibres can be co-ordinated and programmed in three or more axes, designed to fabricate composite structures or laminates from fibrous or filamentary materials, and co-ordinating and programming controls;

- France
- Germany
- Italy
- Japan
- Netherlands
- Russian Federation
- United Kingdom
- United States

Global Production



Nature and Purpose: Filament winding machines and fiber/tow placement machines lay fibers/tows coated with an epoxy or polyester resin onto rotating mandrels in prescribed patterns to create high strength-to-weight ratio composite parts. The filament winding machines look and operate somewhat like a lathe. Fiber/tow placement machines come in many different configurations that include gantry, column or robotic depending on the size and geometric complexity of the part. After the winding operation is completed, the part requires some form of curing to set the epoxy or resin system. The curing is performed in an oven, autoclave or hydroclave.

Method of Operation: Filament winding and fiber/tow placement machines both require mandrels to form the proper geometry for the part to be created. For filament winding, the mandrel is mounted on the machine and rotated. As it spins, it draws continuous fiber from supply spools onto the outer surface of the mandrel in a precise pattern. The continuous fiber may be pre-impregnated or drawn through an epoxy or polyester resin bath. For fiber/tow placement, the mandrel may rotate or be in a fixed position. The head of the fiber/tow placement machine lays down pre-impregnated or dry resin 'filament bands' from spools onto the mandrel while applying heat and pressure. Unlike the filament winding machine the 'filament bands' are often cut at predetermined position based on the part geometry. After winding, the mandrel and the part built up on it are removed from the machine, and the part is cured before the mandrel is removed. Common types of mandrels include water-soluble spider/plaster mandrels; and segmented, collapsible mandrels. Large motor cases for solid rocket motors are usually manufactured on water-soluble sand mandrels. Non-removable liners are sometimes also used. For example, metal-lined pressure vessels are made by using a metal liner as the mandrel, which is simply left inside the wound case.

Typical Missile-Related Uses: Filament winding machines and fiber/tow placement machines are used to make rocket motor cases, propellant tanks, pressure vessels, and payload shrouds. The high strength and low weight of the resulting structures make increased missile ranges and payload weights possible.

Other Uses: Filament winding machines and fiber/tow placement machines are used to produce aircraft parts such as tail stabilizers, parts of wings, and the fuselage. They can be used to make liquid natural gas tanks, hot water tanks, compressed natural gas tanks, golf club shafts, tennis racquets, and fishing rods.

Appearance (as manufactured): The size of filament winding machines and fiber/tow placement machines varies with the size of the part to be made. Filament winders used to manufacture parts 10 cm in diameter measure about 1 m x 2 m x 7 m and can fit on a tabletop. Winders for large components, such as large rocket motor segments, are approximately 3 m diameter and 8 m in length and weigh several tons (Figure 61). Advanced winding machines are computer numerically controlled and can wind complex shapes to meet special requirements.

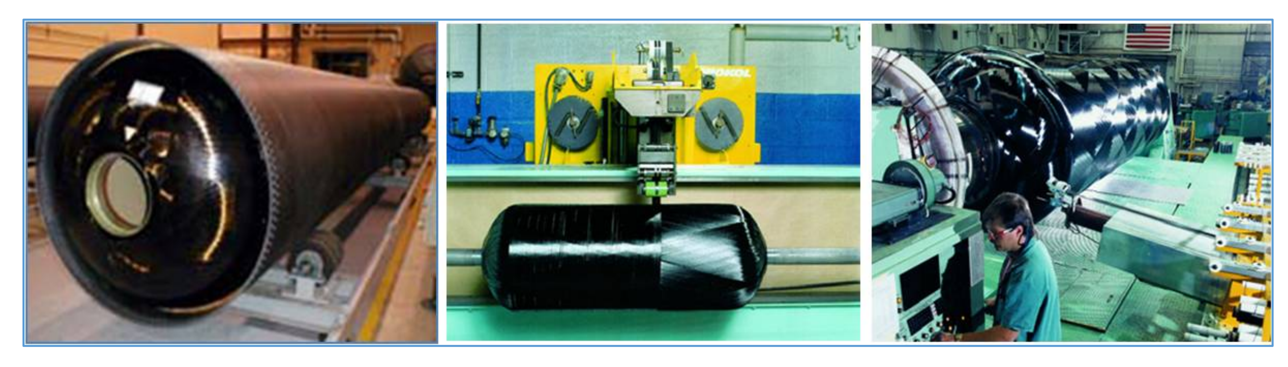


Figure 61: ***Left:*** **A graphite epoxy case produced using an advanced filament winding machine. (ATK)** ***Center:*** **Tabletop filament-winding machine. (Thiokol Corp.)** ***Right:*** **A filament-winding machine with multiple spools of fiber. (Ibid)**

Appearance (as packaged): The size of filament winding machines dictates their packaging. Smaller machines are crated in shock-absorbing containers or attached to cushioned pallets isolated from other packages. Larger machines are disassembled for shipping and reassembled on-site, and their components are packaged separately in crates or on pallets.

6.B.1.b. 'Tape-laying machines' of which the motions for positioning and laying tape can be co-ordinated and programmed in two or more axes, designed for the manufacture of composite airframes and missile structures;

Note:

For the purposes of 6.B.1.a. and 6.B.1.b., the following definitions apply:

1. A 'filament band' is a single continuous width of fully or partially resin-impregnated tape, tow, or fibre. Fully or partially resin-impregnated 'filament bands' include those coated with dry powder that tacks upon heating.

2. 'Fibre/tow-placement machines' and 'tape-layering machines' are machines that perform similar processes that use computer-guided heads to lay one or several 'filament bands' onto a mold to create a part or a structure. These machines have the ability to cut and restart individual 'filament band' courses during the laying process.

3. 'Fibre/tow-placement machines' have the ability to place one or more 'filament bands' having widths less than or equal to 25.4 mm. This refers to the minimum width of material the machine can place, regardless of the upper capability of the machine.

4. 'Tape-layering machines' have the ability to place one or more 'filament bands' having widths less than or equal to 304.8 mm, but cannot place 'filaments bands' with a width equal to or less than 25.4 mm. This refers to the minimum width of material the machine can place, regardless of the upper capability of the machine.

•France	•Germany
•Italy	•Japan
•Netherlands	•Russian Federation
•United Kingdom	•United States

Global Production



Nature and Purpose: Tape-laying machines come in many sizes and configurations. Machines used to manufacture airframes and missile structures resemble gantry-style milling machines. Instead of removing material they place ‘filament bands’ on a mandrel. Candidate parts for using these machines have sufficiently gradual contours or angles to allow the use of thick or wide ‘filament bands’. These machines differ from fiber/tow placement machines in the geometric complexity of the parts produced; fiber/tow placement machines are required when parts have highly concave or convex surfaces and blended areas where narrower ‘filament bands’ need to be placed.

Method of Operation: Tape-laying machines operate by placing unidirectional ‘filament bands’ of prepreg onto a mandrel that defines the shape of the part being produced. Unlike filament winding machines, these ‘filament bands’ are cut during the layup process at predefined points usually driven by the part geometry or design requirements. Structures with little curvature use tapes with larger widths (up to about 30 cm). Structures with moderate to large curvature use tapes in smaller widths or apply them on the bias with respect to the principal direction of curvature.

Typical Missile-Related Uses: Tape-laying machines are used to make RV heat shields, control surfaces, interstage bulkheads and other skins with moderate curvature that are not bodies of revolution.

Other Uses: Tape-laying machines are used extensively in the military and commercial aerospace industries for wing skins and fuselage sections where precise orientation of the 'filament bands' is required for strength and safety. The parts tend to be large and either flat or with moderate curvature.

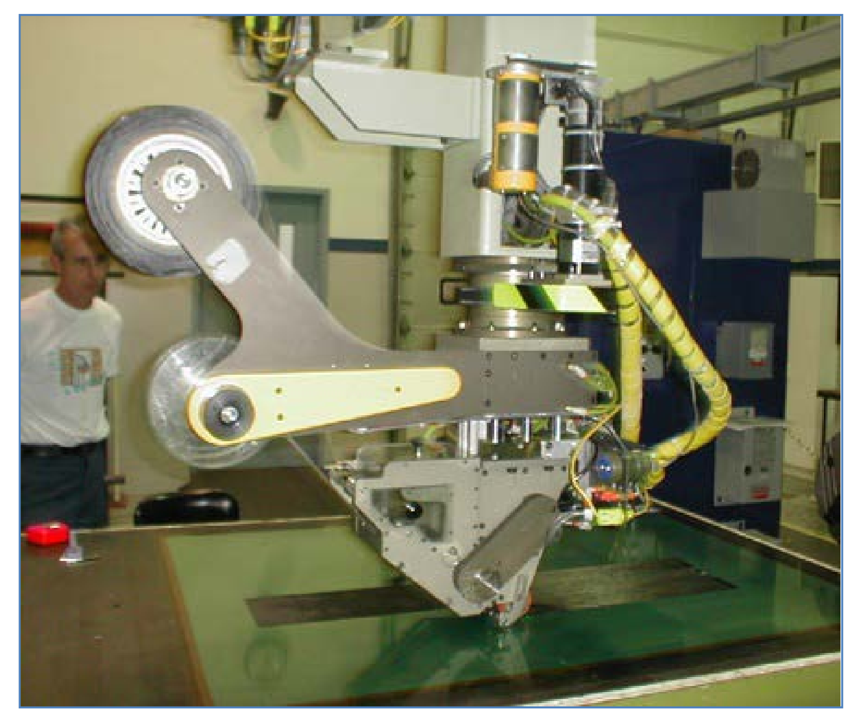


Figure 62: An automated tape-laying machine head. (Automated Dynamics)

Appearance (as manufactured): The size of tape-laying machines varies with the size of the required parts. Machines are either operator assisted or Computer Numerically Controlled (CNC). CNC machines have a keyboard to input data for the desired composite lay-ups. The flatbed, which is the dominant feature of the machine, measures 1 m to 2 m in length for the manufacture of small parts and 10 m for very large parts. The weight of large machines with a steel table and gantry could be 1,000 to 2,000 metric tons. An example of a tape-laying machine is shown in Figure 62.

Appearance (as packaged): The size of tape-laying machines dictates their packaging. Smaller machines are crated in shock-absorbing containers or attached to cushioned pallets isolated from other packages. Larger machines are disassembled for shipping and reassembled on-site, and their components are packaged separately in crates or on pallets.

6.B.1.c. Multi-directional, multi-dimensional weaving machines or interlacing machines, including adapters and modification kits for weaving, interlacing or braiding fibres to manufacture composite structures;

Note:
6.B.1.c. does not control textile machinery not modified for the end-uses stated.

- France
- Germany
- Japan
- Netherlands
- United States

- Textile machinery not controlled and readily modified for low-end use can be purchased in many countries.

Global Production



Nature and Purpose: Multi-directional, multi-dimensional weaving machines are used to interlink fibers to make complex composite structures. Braiding machines provide a general method of producing multi-directional material preforms. The purpose is to systematically lay down fibers along anticipated lines of stress in complex preform configurations, thus making the parts stronger and lighter-weight than otherwise possible.

Weaving machines require intricate handling mechanisms to interlink fibers, with spools and rotation/movement mechanisms integral within each machine. Some machines, particularly those used for RV heat shields, are mounted on a bed and rely on rigid rods in at least one direction to stabilize the weave geometry. For weaving machines used to manufacture three-dimensional (3-D) polar preforms, the basic network construction needed to do the weaving includes pierced plates with specially designed hole patterns, plain plates, metallic rods, knitting needles, retraction blades, and, if the process is fully automated, the machinery required to operate the knitting needles and retraction blades. The sub-elements for other types of weaving depend on the specific design of the machine.

Method of Operation: In one system, a weaving mandrel is first installed onto the machine. As the mandrel assembly rotates, circumferential fibers are continuously laid down at the weaving site by a tubular fiber delivery system, which includes fiber-tensioning devices and missing-fiber sensors. At each pie-shaped corridor formed by the weaving network, a radial knitting needle traverses the corridor, captures a radial fiber at the inside of the port, and returns to the outside of the port, where it makes a locking stitch that prevents movement of the radial fiber during subsequent operations. This process is continued and completed by final lacing.

Braiding machines intertwine two or more systems of fibers in the bias direction to form an integrated structure instead of lacing them only in a longitudinal direction as in weaving. Thus, braided material differs from woven and knitted fabrics in the method by which fiber is introduced into the fabric and in the manner by which the fibers are interlaced.

Typical Missile-Related Uses: Multi-directional, multi-dimensional weaving machines are used to make critical missile parts such as RV nose tips, rocket motor cases and rocket nozzles that are exposed to high temperatures and stress.

Other Uses: Weaving machines are used to make a broad range of complex composite parts such as aircraft propellers, windmill spars, skis, utility poles, and sporting goods.



Figure 63: ***Left:*** **A 144 carrier overhead gantry braiding machine. (Wardwell Braiding Machine Co.)** ***Right:*** **Prototype of a multi-directional weaving machine under development. (MD Fibertech Corp)**

Appearance (as manufactured): A weaving machine has a work area on a rotating table with a network of rods penetrating pierced plates around which the fiber is woven. The work area is surrounded by spooled fiber dispensers and by weaving and lacing needles. The drive motors, cams, and push rods that do the weaving are also mounted on the main frame of the machine.

Weaving machines used to make small parts might measure 2 m in length and 1 m in width. Those used to make large parts might be 10 m long if arranged horizontally or 10 m high if arranged vertically. Braiding machines can be either floor-mounted or have an overhead gantry supporting the spindle on which the preform is made. In either configuration, the fiber is fed to the spindle radially through a large wheel centered on the spindle. The control panel is located at the center of the gantry in order to monitor preform development.

Appearance (as packaged): The packaging of weaving machines depends on their size. Smaller machines can be completely encased in packing crates. The components of larger machines are disassembled for shipping and reassembled on-site, and are packaged separately in crates or on pallets. It is likely that one large crate contains the machine frame. All components are suitably protected from shock and vibration during transportation and handling.

6.B.1.d. Equipment designed or modified for the production of fibrous or filamentary materials as follows:

1. Equipment for converting polymeric fibres (such as polyacrylonitrile, rayon or polycarbosilane) including special provision to strain the fibre during heating;

- Germany
- Japan
- Russian Federation
- United Kingdom
- United States

Global Production



Nature and Purpose: Polymeric fibers are precursors to manufacturing carbon and ceramic fibers. The quality of these precursors directly impacts the material properties and the yield variance of the final product. The conversion from a polymer to a carbon or ceramic fiber occurs by heating and stretching the precursor within a controlled atmosphere. The equipment controlled under this section heats, stretches and controls the atmosphere in which the fiber is processed.

Method of Operation: The general process for manufacturing carbon fiber from polyacrylonitrile (PAN) is as follows.

The PAN fiber on bobbins is loaded into a creel that feeds the production line. The polymeric fiber is spread flat forming a tow band or sheet prior to entering the oxidation ovens. Crosslinking of the polymer chains begin at this step. The density of the fiber increases and the carbon content is 50 to 65 percent. Next, carbonization takes place in high temperature furnaces that provide an inert atmosphere (nitrogen or argon) to prevent oxygen from degrading the fiber. As the fiber passes through these furnaces it loses weight and volume. Depending on the number of carbonization furnaces and the final exposure temperature the fiber’s carbon content can vary between 93 and 99 percent. Throughout the process the tension or stretch of the fiber is critical to the final product’s mechanical properties.

Typical Missile-Related Uses: The equipment is used to convert and strain polymeric fibers to produce fibers used in missile applications where great strength and low weight are paramount. These fibers are used in missiles to improve the strength of the motor case, fairing, and propellant tank while reducing weight and thereby increasing the range and payload capacity of the missile.

Other Uses: The equipment is used to convert polymeric fibers for many uses, including aircraft structures, tires, golf clubs, and boat hulls.

Appearance (as manufactured): Describing the appearance of the equipment used to convert polymeric fibers is difficult because of the variety of ways in which equipment layout can occur. The layout is usually tailored to the production building and covers considerable floor space. The most noticeable items are the many precision rollers and the mechanisms for their control. The rollers are typically 8 cm to 20 cm in

diameter by 30 cm to 120 cm long, with their size related to the ovens in which they are to be used. Drive rollers are used to slowly pull the precursor fiber through an oven under controlled tension. The drive rollers are typically made of polished stainless steel or chrome-plated steel and are either driven in a manner to keep the filaments at a constant tension or are driven at a preprogrammed rate to elongate the filaments as a part of the process. Thus, rollers may be driven by individual motors on their shafts or proportionately driven by gears from one motor-driven shaft.

The machinery is designed to allow the fiber to make several passes through the heated zone with precise control of the speed of the fiber, the temperature in each zone of the furnace, and the tension on the fiber. The fiber must pass through several of these furnaces because the process requires a wide variety of different reactions. A typical fiber-drawing oven system has many rollers and isolated heating zones in the furnace. The size of the equipment varies widely.

Typically, the vertical-treating oven systems are used for higher temperature thermal treatment. However, the diverse treatments required to produce a carbon or other refractory fiber from a polymeric fiber demand that several pieces of equipment be used. Typical requirements include low-temperature furnaces with critical textile handling systems and high-temperature ovens with fiber handling capability for conversion of the fiber to its final state.

Appearance (as packaged): The ovens, furnaces, and processing equipment needed to produce carbon fibers vary in packaging depending on their size, weight, and sensitivity to environmental factors. Generally, laboratory versions of the equipment can be completely crated and shipped by rail or truck. Larger furnaces designed for commercial use generally have to be shipped in component units and assembled on-site. However, some of the furnaces can be of such large diameter that they must be specially handled as oversize cargo. The weight for these larger furnaces approaches 1,000 metric tons or more.

6.B.1.d.
2. Equipment for the vapour deposition of elements or compounds on heated filament substrates;

- Germany
- Japan
- Russian Federation
- United Kingdom
- United States

Global Production



Nature and Purpose: The equipment for vapor deposition applies a very thin interface coating to filaments. These interface coatings change the properties of the filaments. Metallic coatings are conductive and add abrasion resistance; some ceramic coatings protect fibers from reacting with either the atmosphere or adjacent materials. Coatings may also improve the eventual compatibility of the fibers with a matrix material, as is the case for some metal matrix composites.

Method of Operation: This equipment provides a suitable partial vacuum environment for condensing or depositing a

coating on filaments. The vapor deposition process has several variations; two of the most important basic processes are chemical vapor deposition (CVD) and physical vapor deposition (PVD).

The CVD process deposits solid inorganic coatings from a reacting or decomposing gas at an elevated temperature. Sometimes this process occurs in a radio-frequency-generated plasma to ensure thermal uniformity and improve the quality of CVD coatings in a process called plasma-assisted CVD (PACVD). The PVD processes use sputtering, evaporation, and ion plating to deposit the coating on the filaments. The equipment for PVD is similar to the equipment for CVD except that the chamber does not have to operate at a high temperature and does not require a reactive gas supply.

Typical Missile-Related Uses: The equipment for the deposition of elements on heated filaments produces fibers used in rocket motor nozzles and RV nose tips.

Other Uses: This equipment coats fibers used in jet aircraft. PACVD is currently an important technique for the fabrication of thin films in the microelectronics industry and has been applied to the continuous coating of carbon fibers.

Appearance (as manufactured): CVD and PVD chamber configurations vary greatly. Some are long tubes with seals at each end that permit the passage of filaments but not gases. Others are large chambers, 2 m to 3 m on a side, with room enough to hold the filament spools, filament guide equipment including spreading and tensioning rollers, a hot zone if needed, and the reactant gases. Because of this variation, the only standardized and readily recognizable parts of the equipment are the gas supply system, a large power supply, vacuum pumps, and possibly the instrumentation that controls the temperature. In all cases, the power supplies are of substantial size and weight, typically greater than 0.6 m x 0.9 m x 1.5 m with water inlets for cooling, pumping, and safety cutoffs. PACVD equipment looks like a conventional CVD or PVD system except that it has a radio-frequency (RF) power supply to produce the plasma.

Appearance (as packaged): Packaging varies depending on size, weight, and sensitivity to environmental factors. Generally, laboratory versions of the equipment can be completely crated and shipped by rail or truck. However, even laboratory versions generally have components packaged separately so that the textile spools, motors, and special glassware can receive adequate protection. Larger systems designed for commercial use are usually shipped as subassemblies or components and assembled on-site.

6.B.1.d.
3. Equipment for the wet-spinning of refractory ceramics (such as aluminium oxide);

Nature and Purpose: Wet-spinning equipment is used to produce long filaments from a mixture of liquids and solids. These filaments are further processed to produce high-strength, high-temperature ceramic filaments for ceramic or metal-matrix composites.

Method of Operation: In wet-spinning of refractory ceramics, a slurry of fiber-like particles is physically and chemically treated and drawn into a filament through an orifice called a spinneret. The chamber in which the filaments are created either rotates or contains an internal mixing device, either of which

- Germany
- Japan
- Russian Federation
- United Kingdom
- United States

Global Production



produce the vortex in which filament entanglement occurs. The material emerges from the spinneret and is solidified by a temperature or chemical change, depending on the binder system used in the wet bath surrounding the spinneret. The bath supports and stabilizes the filaments produced as they cool.

Typical Missile-Related Uses: The wet-spinning equipment is used to manufacture high-grade ceramic fibers for missile nose tips and rocket engine nozzles. Such fibers are also used to produce some ramjet and turbojet engine parts applicable to cruise missiles.

Other Uses: Wet-spinning equipment is used to make ceramic fibers for producing engine parts for small gas turbine engines, chemical processing containers, and high-temperature structural applications. Ceramic fibers or whiskers can be combined with other composite materials to enhance strength and high-heat resistance in many commercial products.

Appearance (as manufactured): A major component of wet-spinning equipment is the cylindrical chemical reaction chamber. Although glassware is acceptable for laboratory and prototype wet-spinning equipment, stainless steel or glass-lined reaction chambers are used for production grade wet-spinning equipment. Typically, the chamber is vertically oriented and tapered at the bottom, where the dies that extrude the filaments are located.

Other equipment associated with the chemical reaction chamber includes a cylindrical vessel (much longer than its diameter) that contains the chemical slurry from which the filament is produced; a pressure gauge and gas exhaust line attached to the vessel; a tube assembly containing sections of both fixed and rotating glass tubes; a ball valve connected to the fixed glass tube; a motor and controller for driving the rotating tube; and a snubber roller and take-up reel for the finished filaments.

Appearance (as packaged): Packaging is typical of any similarly sized industrial equipment. Generally, fully assembled laboratory versions of the equipment can be crated and shipped by rail or truck. Components of larger equipment designed for commercial use are shipped in separate boxes or crates and assembled on-site.

6.B.1.e. Equipment designed or modified for special fibre surface treatment or for producing prepregs and preforms, including rollers, tension stretchers, coating equipment, cutting equipment and clicker dies.

- France
- Germany
- Sweden
- Switzerland
- United Kingdom
- United States

Global Production



Nature and Purpose: Fiber surface treatment and prepregging equipment are used to prepare fibers for making high quality composite materials. Surface treatments improve adhesion by increasing the fiber surface area; prepregging adds enough resin to the fiber (or filaments, roving, or tape) for curing it into a composite.

Method of Operation: The fiber filaments, roving, or tape to be processed in surface treatment equipment is passed through a series of electrochemical or electrolytic baths made up of liquid reactants for etching or roughing the fibers and adding reactive chemical groups. After surface treatment a special coating called sizing is applied to the fiber filaments which protects the fiber during handling and post-sizing operations such as weaving. Materials are fed on rollers through a bath of reactants in a simple dip operation. The number and speed of rollers in the bath determines how long the part is etched or how much sizing is retained. Heaters are used to modify the reactivity of the etch system, to control the viscosity of the sizing bath, to promote chemical reactions that make the sizing stable, and to dry the product.

Typical Missile-Related Uses: This equipment is used to surface treat various fibers used in the manufacture of missile parts in order to improve bonding to missile components such as nose tips, motor cases, and exhaust nozzles.

Other Uses: This equipment is identical to that used to make the fibers for all commercial applications of composite technology from boat hulls to golf clubs.

Appearance (as manufactured): A laboratory bench with small rollers and heater guns is the only equipment needed to treat or prepreg fiber on a prototype basis. For production-level activity, the textile handling equipment is much larger so that multiple lines can be treated at the same time. The process may also involve heater stacks many stories high. All of the systems have rollers for keeping the textile material moving, maintaining tension on the fiber, and squeezing out excess liquid, as well as an oven with a complex path over the rollers so that the filaments traverse the oven several times.

Appearance (as packaged): The packaging of the equipment, with the exception of small laboratory apparatus, usually requires that components be shipped separately and assembled on-site. The reason is that the base, the vats for holding chemicals, and the textile handling apparatus require different types of packaging protection. The vats for chemicals can be packaged in simple corrugated boxes, but the rollers, which have a precision or special surface finish to avoid damaging the filaments, need cushioning and rigid mounting in substantial crates. Electrical control equipment, if included, will be packaged like other fragile electronics.





Figure 64: ***Left:*** **A prepreg machine constructed by the Composite Materials Group for the production of prepreg materials using fibers and resins. (Katholieke Universiteit Leuven)** ***Right:*** **A machine adding resin to seven lines of roving. (Hunting Engineering, Ltd.)**

Note:
Examples of components and accessories for the machines specified in 6.B.1. are moulds, mandrels, dies, fixtures and tooling for the preform pressing, curing, casting, sintering or bonding of composite structures, laminates and manufactures thereof.

6.B.2. Nozzles specially designed for the processes referred to in 6.E.3.

- France
- Germany
- Russian Federation
- United States

Global Production



Nature and Purpose: Nozzles for pyrolytic deposition direct an unreacted gas to a surface on which deposition is desired. The nozzles must be movable or located so they can cover the entire surface within a CVD furnace at high temperature and pressure.

Method of Operation: Nozzles used in CVD furnaces deliver cold, unreacted gas to the surface being treated. The gas must be both unreacted so that the coating occurs on the intended surface rather than on the inside of the nozzle, and close to the surface to be treated so that the surface and not the walls of the furnace get sprayed. A nozzle is like a paint spray gun, which must be close to the part being painted.

Typical Missile-Related Uses: These nozzles are required parts of pyrolytic deposition equipment used to make critical, highly heat-tolerant parts such as rocket nozzles, throat inserts, and RV nose tips.

Other Uses: These nozzles are used to make highly heat-tolerant parts for jet engines.

Appearance (as manufactured): Nozzles for CVD furnaces are designed to tolerate high furnace temperatures either by construction from high temperature-resistant material such as graphite or by water-cooling. Nozzle dimensions are approximately half the width of the furnace. Small nozzles are typically made of graphite because it is inexpensive, easily replaced, and lightweight (approximately 0.5 kg to 2.5 kg). Larger nozzles for production furnaces are often made of metal, require water-cooling, may have integral attachment flanges, and weigh upwards of 25 kg.

Nozzles are made in varying lengths, which depend on the size of the furnace and the surface. The larger, more complex, water-cooled nozzles are up to 1.5 m long, with their tubular portion 20 cm in diameter. However, because some portion of most nozzles is custom designed, there is no standard shape or size.

Appearance (as packaged): Packaging for the nozzle and pyrolytic deposition equipment is suitable for preventing damage to a highly durable pipe with somewhat fragile valves and fittings. Typically, several nozzles are shipped together in well protected packaging separate from any large furnace shell.

6.B.3. Isostatic presses having all of the following characteristics:
a. Maximum working pressure equal to or greater than 69 MPa;
b. Designed to achieve and maintain a controlled thermal enviroment of 600°C or greater; and
c. Possessing a chamber cavity with an inside diameter of 254 mm or greater.

- France
- Germany
- Russian Federation
- United States

Global Production



Nature and Purpose: Isostatic presses are used to infuse carbon into a porous carbon preform of a rocket nozzle or RV nose tip under high temperature and pressure. This process, referred to as densification, virtually eliminates voids in the preform and improves the mechanical and physical properties of the treated object.

Method of Operation: The object to be processed is placed in the appropriate chamber and lowered into the hot zone of the furnace. All water and electrical connections are made and all process instrumentation is connected before the lid is lowered into the furnace and sealed. As the object is heated, it is subjected to high pressure until the proper densification has been achieved. Reaction products are removed by internal plumbing so they do not come into contact with the heater elements.

Typical Missile-Related Uses: Isostatic presses are used in making nose tips for RVs and nozzle inserts for rocket motors.

Other Uses: These presses are used in diffusion bonding of similar metals, diffusion bonding of dissimilar metals to form laminates (silver-nickel-silver or copper-stainless), and provision of seamless joints. They are used in various powder metallurgy applications. They are also used to improve the quality of metal castings and forgings by hydrostatically forcing defects to close and bond shut.

Appearance (as manufactured): Isostatic presses intended for densification are specially modified to operate while a pyrolysis reaction is occurring. A typical laboratory-size system has five main components: a pressure vessel, an internal furnace, gas handling, electrical, and auxiliary systems. The pressure vessel is usually a vertical, thick-walled cylinder with a removable, high-pressure closure, or plug, at either the upper or lower ends (Figure 65). Some presses have horizontal pressure vessels.

The furnace sits inside the pressure vessel and provides the heat and space required for the densification process. Heating elements made from graphite, molybdenum or nickel/chrome are used to heat the part by direct radiation or to heat the inert gas which then heats the part by convection.





Figure 65: ***Left***: **A laboratory sized isostatic press. (ESPI)** ***Right:*** **A laboratory sized hot isostatic press. (Abra Fluid AG)**

The gas handling equipment supplies the inert gas, usually argon, to apply a uniform force onto the part being densified. Gas pressure is achieved using a compressor. Operating pressures can range from 10 MPa up to 300 MPa.

The electrical and auxiliary systems include an instrument panel with typical industrial temperature and pressure control and recording instrumentation. A computer for entering process parameters required to control the operation of the press is included.

The press may be surrounded by an energy-absorbing shield. This shield may be engineered at the plant where the system operates and often involves installing the chamber below ground. The pressure vessel also has an isolation chamber and plumbing to be sure that gas from the process zone is removed from the exhaust and does not flow to the heater zone.



Figure 66: ***Left:*** **Side view of a large isostatic press. (Engineered Pressure Systems, Inc.)** ***Center and Right:*** **Two different views of an alternative shipping crate for an isostatic press. (Engineered Pressure Systems, Inc.)**

Appearance (as packaged): The components of an isostatic press system are likely to be shipped separately and assembled at the final work destination. Packaging varies with the requirements of the purchaser, but wooden pallets and crates with steel banding and reinforcement are common (Figure 66). Larger chambers are very heavy because of the thick walls and may be packaged in a cylindrical wooden crate with wide steel banding.

6.B.4. Chemical vapour deposition furnaces designed or modified for the densification of carbon-carbon composites.

- France
- Germany
- Russian Federation
- United Kingdom
- United States

Global Production



Nature and Purpose: CVD furnaces are used to infuse carbon into a porous carbon preform of a rocket nozzle or RV nose tip. This process, referred to as densification, virtually eliminates voids in the preform and improves the mechanical and physical properties of the treated object. The final properties of carbon-carbon composites is highly dependent on the type and orientation of the carbon fibers in the preform and the process parameters used for densification.

Method of Operation: CVD furnaces use either isothermal or thermal-gradient processes for densification. The object to be processed is placed in the appropriate chamber and lowered into the hot zone of the furnace. All gas, water, and electrical connections are made, and all process instrumentation is connected before the lid is lowered into the furnace and sealed. Next the furnace is evacuated of air and heated to around 1,000 °C. Then the hydrocarbon gas, such as natural gas or methane, is introduced. The gas diffuses into the preform, separates into component molecules, and deposits pyrolytic carbon into the preform filling the voids. The process sequence of heating and supplying the deposition gases is automated. For the isothermal process the preforms are held at this uniform temperature for 30 to 40 days until the desired density and porosity of the composite is obtained.

Typical Missile-Related Uses: CVD furnaces are used to make carbon-carbon rocket nozzles and nose tips. Carbon-carbon pieces are lightweight and strong, and can increase system performance.

Other Uses: CVD furnaces are used in coating optics, densifying friction materials for aerospace braking systems, and cutting tools; in coating and polishing precision surfaces; and in making semiconductors.

Appearance (as manufactured): CVD furnaces are large, double-walled, cylindrical vessels with gas-tight closures. Typical CVD furnaces are large because they house an internal heat zone, electrically driven heaters, and insulation. Furnaces smaller than 1.5 m in height and 1 m in diameter are considered laboratory scale and are barely able to process a single nose tip or rocket nozzle insert. Process production sizes are larger than 2 m in height and 2 m in diameter. These furnaces have several ports: at least one large port for power feeds, others for instrumentation, and, when temperatures are measured by optical

or infrared pyrometers, one or more view-ports.

CVD furnaces are double-walled so that they can be water-cooled during operation. Power cables are large and may also be water-cooled. The actual retort is housed inside the furnace and is heated by a graphite induction or resistive heater to temperatures of between 2,200 °C and 2,900 °C.





Figure 67: *Left:* A large scale custom CVD furnace which inductively heats graphite to temperatures in the 2800 °C range. (CVI) *Right:* A large CVD furnace. (Seco Warick)

A custom designed CVD furnace is shown in Figure 67, consisting of several components, including an impregnation vessel for adding a liquid resin to the preform; instrumentation and control panels (foreground); and a pressure-carbonization furnace.

Appearance (as packaged): Packaging consists of pallets and crates for each part because of the large size and weight of the equipment. The large lids, the power supply, and the body of the furnace often have built-in lift points or rings to help move and assemble them.

6.B.5. Equipment and process controls, other than those specified in 6.B.3. or 6.B.4., designed or modified for densification and pyrolysis of structural composite rocket nozzles and re-entry vehicle nose tips.

Nature and Purpose: Specialized equipment and process controls are essential for the densification and pyrolysis necessary to produce structural composites used for rocket nozzles and RV nose tips. Specially designed software often is required to operate the equipment and/or control the processes to produce these structural composites. Manufacturing composite parts from this type of material usually requires cycling through various process conditions such as high temperature and/or pressure. Precise control of the conditions during the cycles and their timing is key to ensuring acceptable results. This item also requires documentation (technical data) of the various process parameters needed to produce these materials.

Method of Operation: Equipment, process controls, and software for densification and pyrolysis are used throughout the manufacturing process for structural composites to handle, process, and finish the material and the resulting products (i.e., rocket nozzles and RV nose tips).

Typical Missile-Related Uses: This equipment and process controls, with associated software, are used to produce structural composites (including carbon-carbon items) used for rocket nozzles and RV nose tips.

Other Uses: These items are also used for diffusion bonding of metals, in powder metallurgy, and for treating metal components.

Appearance (as manufactured): The equipment resembles other manufacturing equipment but can include smaller (research size) items. Process controls can take the forms of technical data such as paper, magnetic, or other media.

Appearance (as packaged): Larger pieces of equipment may be shipped as components, while smaller items may be shipped assembled. These items are usually shipped in crates or on pallets in a similar manner to other industrial equipment. Process controls (including technical data) are shipped like other information on paper, magnetic, or other media. Software and technical data may be included in the shipping containers with its respective equipment.

6.C. Materials

6.C.1. Resin impregnated fibre prepregs and metal coated fibre preforms, for the goods specified in 6.A.1., made either with organic matrix or metal matrix utilising fibrous or filamentary reinforcements having a specific tensile strength greater than 7.62 x 10^4 m and a specific modulus greater than 3.18 x 10^6 m.

Note:
The only resin impregnated fibre prepregs specified in 6.C.1. are those using resins with a glass transition temperature (Tg), after cure, exceeding 145°C as determined by ASTM D4065 or national equivalents.

Technical Notes:
1. In Item 6.C.1. 'specific tensile strength' is the ultimate tensile strength in N/m^2 divided by the specific weight in N/m^3, measured at a temperature of (296 ± 2)K ((23 ± 2) °C) and a relative humidity of (50 ± 5) %.
2. In Item 6.C.1. 'specific modulus' is the Young's modulus in N/m^2 divided by the specific weight in N/m^3, measured at a temperature of (296 ± 2)K ((23 ± 2) °C) and a relative humidity of (50 ± 5) %.

- France
- Germany
- Russian Federation
- United Kingdom
- United States

Global Production



Nature and Purpose: Prepregs and preforms are the basic materials from which lightweight, high strength composite structures are made. Prepreg is the name given to a cloth-like material made of fibers and impregnated with resins. Prepregs are assembled over a form (e.g., a mandrel or mold) into the desired shape. Sometimes several layers are used to create laminates. Preforms are solid, three-dimensional, fiber structures with the same shape and roughly the same dimensions as the desired part and impregnated with resin. After curing, the preform is machined into the final configuration. Usually, the materials of interest are then cured to temperatures above 175 °C to complete polymerization of the thermoset resin and to achieve a high glass transition temperature.

Method of Operation: Prepregs and preforms are precursors to the composites and laminates that can be used almost anywhere in rockets and UAVs, including cruise missiles. Uses include solid rocket motor cases, interstages, wings, inlets, nozzles, heatshields, nosetips, structural members, and frames.



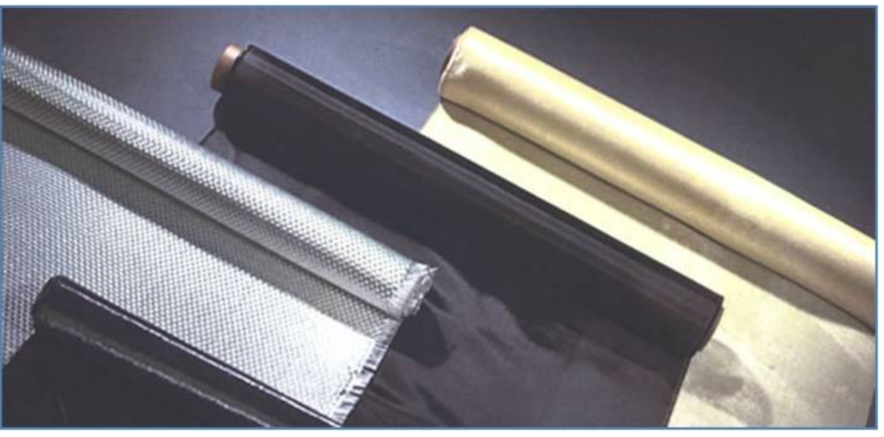


Figure 68: *Left:* A nose cone for a space launch vehicle manufactured using advanced prepreg techniques. (ATK) *Right:* Prepreg material used in the manufacture of lightweight, high-strength composite aerospace and defense structures. (Ibid)

Typical Missile-Related Uses: These materials are used to produce structural composites (including carbon-carbon items) used in a range of aerospace and defense applications, including rocket nozzles, missiles, satellite structures and RV nose tips.

Other Uses: Prepregs and preforms allow composite structures to be formed into almost any shape to meet requirements. They are used in both civilian and military aircraft, recreational products (such as equipment for water sports, skis and golf clubs), and in infrastructure and industry. They also have medical application in the design of prosthetic limbs and surgical devices.

Appearance (as manufactured): Prepregs are textile products that are impregnated with a pliable resin. They are manufactured in thin filaments, tapes from sub-millimeters to centimeters wide, and fabrics up to a few meters wide. They are usually stored on spools or in rolls, just like yarn or fabric (see Figure 68-right), and look much like non-impregnated yarn.

Although a prepreg can still deform, it is considerably less capable of draping than a fabric, tape, or yarn that has no resin; however, they are all still deformable enough to be shaped into a composite structural part. Prepregs may be used to form the approximate shape of a desired part, called a preform. A nose cone manufactured using advanced prepreg hand layup is shown in Figure 9 - left. After heating and curing, these preforms are machined to their final shapes and finishes.

Appearance (as packaged): Prepreg is shipped in multiple plastic bags with stiffener sheets on both sides of the material to prevent bending, kinking or creasing. The outer bag acts as a vapor/moisture barrier and contains a desiccant to maintain a relative humidity of 50% or less. The fibrous materials must be refrigerated after impregnation with resin. Refrigeration prevents the resin from polymerizing and hardening before the prepreg is used to manufacture composite materials. If the temperature is held at about –20 °C, the shelf life of the prepreg is approximately six months. To maintain sufficiently low temperatures during shipment, the prepreg material is packed in special containers for dry ice cooling (Figure 69), or it is shipped in mechanically refrigerated cargo containers.

6.C.2. Resaturated pyrolised (i.e. carbon-carbon) materials having all of the following:
a. Designed for rocket systems; and
b. Usable in the systems specified in 1.A. and 19.A.1.

- Brazil
- China
- France
- Germany
- India
- Israel
- Japan
- Russian Federation
- Ukraine
- United Kingdom
- United States

Global Production



Nature and Purpose: Carbon-carbon is a composite of carbon fiber, typically made from pitch, rayon or polyacrylonitrile (PAN), in a carbon-dominated matrix. It is usually produced by using a high-content carbon resin as the initial matrix and then driving off the non-carbon elements with high heat. It is lightweight, highly heat resistant, thermal-shock-resistant and malleable for shaping.

Typical Missile-Related Uses: Carbon-carbon materials are used for items such as rocket motor exit cones and nozzles, and RV nose tips, heat shields and leading edges of control surfaces that must resist the effects of high temperatures and ablation.

Other Uses: Carbon-carbon structures are used in military and civilian aircraft applications such as high-temperature brake shoes, and in other applications requiring high strength and low weight such as wing roots. They can also be used for tooling requiring long life in severe, usually high-temperature, manufacturing environments, such as pouring ladles for steel, heaters for very high-temperature furnaces and hot press tools.

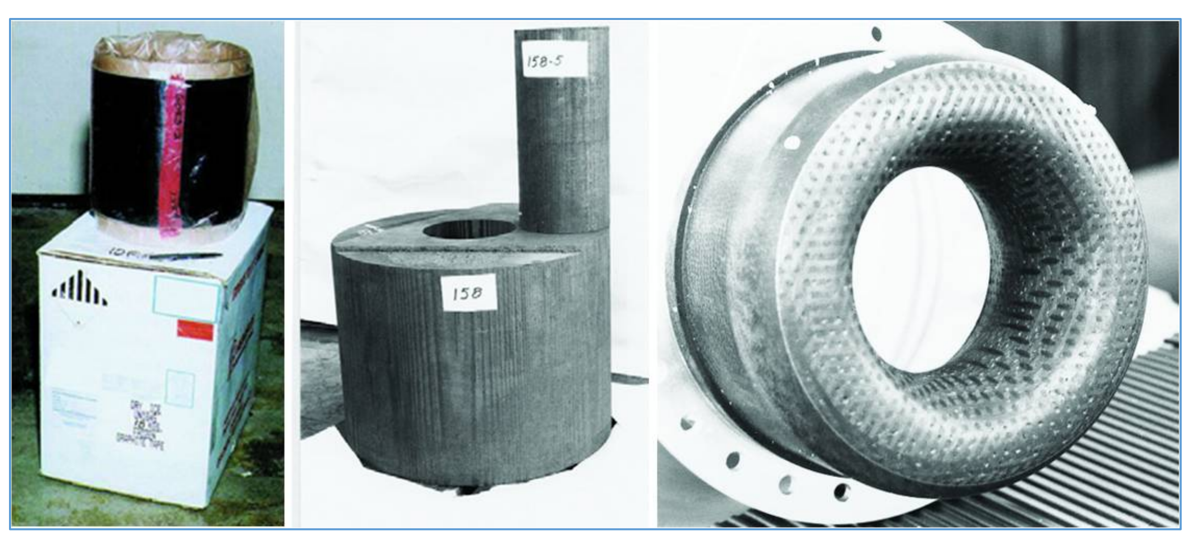


Figure 69 *Left:* Special cardboard container for holding dry ice packing around a carbon fiber prepreg tape spool during shipping. The dry ice is normally contained in a plastic bag packed around the spool. (A Handbook for the Nuclear Suppliers Group Dual-Use Annex, Report No. LA-13131-M (April 1996)) *Middle:* A block of carbon-carbon material ready to be machined into a rocket nozzle. The larger cylindrical block is about 70 cm in diameter. (Ibid) *Right:* A carbon-carbon rocket nozzle throat showing the fabric pattern of the underlying fibers. (Ibid)

Appearance (as manufactured): Typical carbon-carbon materials designed for rocket systems are black and have a patterned surface as a result of textile reinforcement. Nose tips and rocket nozzles are usually machined from blocks or billets.

Appearance (as packaged): Before machining, blocks of carbon-carbon material are rugged enough to be packed in filler and shipped in cardboard boxes. Machined parts require careful packaging because, although the material is resistant to breaking (impact resistant), they can easily be gouged or scraped.

6.C.3. Fine grain graphites with a bulk density of at least 1.72 g/cc measured at 15^0C and having a grain size of 100 x 10^{-6} m (100 μm) or less, usable for rocket nozzles and re-entry vehicle nose tips, which can be machined to any of the following products:

a. Cylinders having a diameter of 120 mm or greater and a length of 50 mm or greater;
b. Tubes having an inner diameter of 65 mm or greater and a wall thickness of 25 mm or greater and a length of 50 mm or greater; or
c. Blocks having a size of 120 mm x 120 mm x 50 mm or greater.

Nature and Purpose: Fine-grain recrystallized bulk graphite is used to create very strong, heat-resistant parts. Graphite is the only known substance that doubles in strength as the temperature increases from room temperature to 2,700 °C. Carbon particles are combined with pitch, a viscous coal tar residue, in a suitable mold and subjected to heat and pressure. The resulting block can be easily machined into the required part. It also has excellent thermal shock resistance and good thermal and electrical conductivity. Pyrolytic graphite is formed by high-temperature vapor deposition but is not widely used because its uneven thermal conductivity causes it to crack when heated.



Figure 70: Various parts machined from fine-grained bulk graphite. (MTCR Equipment, Software, and Technology Annex Handbook, Third Edition (May 2005))

Typical Missile-Related Uses: Fine-grain recrystallized bulk graphite is used for RV nose tips, thrust tabs, and nozzle throats. A typical billet for a nose tip could be as small as several centimeters in each dimension.

Other Uses: Graphite is used in biomedical applications, in nuclear reactors, as a mold in casting and manufacturing metal parts, and for critically-dimensioned furnace fixtures. Graphite is also the preferred material for electrodes for non-wire type electric discharge machining. When infiltrated with metals, graphite is used for brushes in electric motors and as bearings in many mechanical applications.

Appearance (as manufactured): Bulk graphite is a very fine, dark gray to black powder. The density of processed graphite ranges from 1.64 g/cc to 2.7 g/cc, the latter for pyrolytic graphite. Machined parts made from graphite are black and have a gloss dependent on the machining operation. Fine-grain graphite

- Brazil
- China
- India
- Russian Federation
- United States

Global Production

can be distinguished by its lack of surface pitting and some of the fine details that are often in the manufactured product. Graphite is much softer than metals; a ball point pen can dent the surface.

Appearance (as packaged): These materials are packaged to protect their delicate surfaces and often to prevent any surface contamination. Typically, parts are placed in plastic bags or containers, which are packaged in materials normally used for fragile parts (i.e., bubble wrap, foam, etc.).

6.C.4. Pyrolytic or fibrous reinforced graphites usable for rocket nozzles and re-entry vehicle nose tips usable in systems specified in 1.A. or 19.A.1.

- China
- United States

Global Production

Nature and Purpose: Pyrolytic graphite is a unique form of graphite. It is manufactured by decomposing hydrocarbon gas, typically methane, in a vacuum furnace at high temperatures. The result is an exceptionally pure product that nears theoretical density and is highly anisotropic as a result of its layered structure. Through the layers (C plane), it has very low thermal conductivity and acts as an insulator. Along the layers (A-B plane), it has very high thermal conductivity and acts as an excellent conductor. Its thermal, electrical, and mechanical properties are commonly far superior to conventional graphite. Pyrolytic graphite is chemically inert, stable to 3,000 °C, impermeable, self-lubricating, non-dusting, and low weight. However, its uneven thermal conductivity and resultant tendency to crack restricts certain applications.

Method of Operation: To manufacture pyrolytic graphite, the underlying surface material on which the pyrolytic graphite is deposited is heated to a relatively high temperature, ranging from around 1,500 °C to 2,500 °C. Hydrocarbon gas is introduced under elevated temperature and reduced pressure. The result is that the pyrolytic graphite forms an ablative (capable of being burned away in a controlled manner) and insulating layer that can withstand the heat of a rocket motor.

Typical Missile-Related Uses: Pyrolytic graphite has a variety of aerospace and defense applications owing to its ability to withstand extremely high temperatures and thermal shock. In particular, it is used in the design and manufacture of rocket nozzles, on the nose cones of RVs, and in heatshields.

Other Uses: Pyrolytic graphite's exceptional conduction properties offer useful solutions to heat dissipation in high-heat flux semiconductor power electronics, such as RF and wireless, light emitting diodes (LEDs), laser diodes, wide-gap semiconductors, and integrated circuit lids. Pyrolytic graphite is also

used in the manufacture of dies and forming tools that shape semi-molten glass as well as heater elements, sputtering targets, and thermal insulators. Pyrolytic graphite is also used by specialty glass manufacturers, as well as in container glass and stemware.

Appearance (as manufactured): Processed graphite's density varies from 1.64 g/cc to 2.7 g/cc. In powder form, it is dark grey to black in color. In manufactured parts the color is black with the extent of glossiness dependent on the machining process. Surfaces are pitted.



Figure 71: A selection of pyrolitic graphite plates and rods that are high in density, strength, and purity. Note the pitted surface on the large plate on the left of this figure. (Advanced Carbon Technologies, Inc)

Appearance (as packaged): The danger of cracking to which pyrolytic graphite is susceptible requires that it is well packaged, with components usually placed in plastic bags or containers, surrounded by bubble wrap or foam.

6.C.5. Ceramic composite materials (dielectric constant less than 6 at any frequency from 100 MHz to 100 GHz) for use in missile radomes usable in systems specified in 1.A. or 19.A.1.

- China
- France
- Germany
- India
- Japan
- Russian Federation
- United States

Global Production



Nature and Purpose: Ceramic composite materials have strength and thermal properties sufficient for some use as heatshield materials. Unlike carbon-based materials, however, ceramics are insulators and do not conduct electricity while electromagnetic radiation (e.g., radar or radio waves) can pass through them. They are useful in protecting structures and equipment from aerodynamic heating while allowing signals to be transmitted or received.

Silicon-carbide reinforced ceramic composites are suitable for use to 1,200 °C in an oxidizing atmosphere and to a somewhat higher temperature if coated. Silicon-carbide composites reinforced with filaments have high fracture toughness and are considerably lighter than super-alloys. These characteristics make

them useable for missile radomes.

Typical Missile-Related Uses: Ceramic composite materials have been used in ballistic missile RV antenna windows. Silicon-carbide unfired ceramic nose tips are hard and highly heat-resistant; however, because they tend to chip but not break, they are not widely used.

Other Uses: Highly heat-resistant ceramics are used in some gas turbine engines, automobile engines, furnaces, and solar energy receivers. Their uses include grinding rods and balls, furnace tiles, welding cups and nozzles, sandblast nozzles, and a variety of intricate parts for electronic applications. They are a common tooling material for use in manufacturing steps at elevated temperatures. Silicon-carbide reinforced ceramic composites are used in some military jet engines for thrust vector control flaps.

Appearance (as manufactured): Ceramic composite materials used in RV antenna windows generally use ceramic filament reinforcement to prevent thermal-stress-induced failure. A block of three-dimensional (3-D) silica-silica from which antenna windows are made may have a textile pattern evident on all surfaces. This material is often covered with a clear protective coating as a barrier to moisture. A silicon-carbide reinforced ceramic has the same pattern but is dark gray or black. All of these ceramic materials are very hard, much harder than other composites, and have a surface patterned like the textile reinforcement. They may be found in virtually any size between 1 mm discs and 50 cm cubes, which can be cut and ground to the required configuration by diamond tooling.

Appearance (as packaged): Because of their high cost and brittleness, these composites are packed in shock-absorbent materials. Since silica-silica material is also hygroscopic (i.e., it absorbs water), it is also packed in sealed bags of either Mylar or other plastic, often with some type of a desiccant in the larger packing container. Some shippers also fill the sealed bags with dry nitrogen to protect the material from water absorption.

6.C.6. High-temperature ceramic materials as follows:

a. Bulk machinable silicon-carbide reinforced unfired ceramic usable for nose tips usable in systems specified in 1.A. or 19.A.1.;

b. Reinforced silicon-carbide ceramic composites usable for nose tips, re-entry vehicles, nozzle flaps, usable in systems specified in 1.A. or 19.A.1.

c. Bulk machinable ceramic composite materials consisting of an 'Ultra High Temperature Ceramic (UHTC)' matrix with a melting point equal to or greater than 3000°C and reinforced with fibres or filaments, usable for missile components (such as nose-tips, re-entry vehicles, leading edges, jet vanes, control surfaces or rocket motor throat inserts) in the systems specified in 1.A., 19.A.1. or 19.A.2.

Note:

Item 6.C.6.c. does not control "Ultra High Temperature Ceramic (UHTC)' materials in non-composite form.

Technical Note:

'Ultra-High Temperature Ceramics (UHTC)' includes:

1. Titanium diboride (TiB2);

2. Zirconium diboride (ZrB2);

3. Niobium diboride (NbB2);

4. Hafnium diboride (HfB2);

5. Tantalum diboride (TaB2);

6. Titanium carbide (TiC);

7. Zirconium carbide (ZrC);

8 . Niobium carbide (NbC);

9. Hafnium carbide (HfC);

10. Tantalum carbide (TaC).

- Austria
- Brazil
- China
- France
- Germany
- India
- Italy
- Japan
- Russian Federation
- Republic of Korea
- Switzerland
- United Kingdom
- United States

Global Production



Nature and Purpose: Silicon-carbide is a compound of silicon and carbon used in the manufacturing of strong ceramic materials. It is also found in the rare mineral moisssanite. When silicon carbide powder is heated below its melting point in a process called 'sintering', particles adhere to one another to form extremely hard ceramics with high endurance properties. Ceramic composites that have been strengthened by silicon-carbide can withstand temperatures up to 1,200 °C in oxidizing conditions.

Ultra High Temperature Ceramics (UHTC) are a class of materials that can be used in environments that exhibit extremes in temperature, chemical reactivity (oxidation), and erosive attack. UHTCs

may be defined to have melting points in excess of 3,000 degrees Celsius. UHTC composite materials use fibers or filaments of materials such as boron carbide or silicon carbide to reinforce these ceramic materials.

Method of Operation: The critical properties of silicon-carbide are low density, high strength, low thermal expansion, high thermal conductivity, high hardness, excellent thermal shock resistance, and superior chemical inertness.

The higher melting points of UHTC and use of fiber reinforcement (composite) can mitigate some of the traditional drawbacks associated with other ceramics, including a tendency to fracture under thermal stresses and lower oxidation resistance. Among the most promising to date are those that use diborides and carbides of early transition metals, which include titanium diboride (TiB2), hafnium carbide (HfC), and tantalum carbide (TaC).



Figure 72: Silicon carbide coatings have a range of space and aerospace applications, includig protecting graphite material from oxidation. (Schunk Group)

Typical Missile-Related Uses: Silicon-carbide is used in rocket engine nozzles, nose cones, and nozzle flaps. It is also used in ballistic missile RV antenna windows. Its ability to withstand strong thermal shocks allows it to be used as a heat shield and its non-conductivity of electricity and electromagnetic radiation protect spacecraft from heat while allowing continued communications with the ground control station. A silicon-carbide coating protects from oxidation the reinforced carbon-carbon panels along leading edges and nose cones of RVs. Composites containing silicon-carbide and reinforced with filaments are highly durable, heat resistant, and lighter-weight than super-alloys; these characteristics are extremely important in nose cones designed for reentry into the earth's atmosphere.

UHTC composites can be used as nose tips for re-entry vehicles, solid propellant rocket motor throat inserts, jet vanes, and control surfaces. An attractive feature of UHTC composites is lower density (and thus weight) compared to the refractory metals they could replace, such as tungsten and rhenium, thus permitting greater range/payload performance of the missile system.

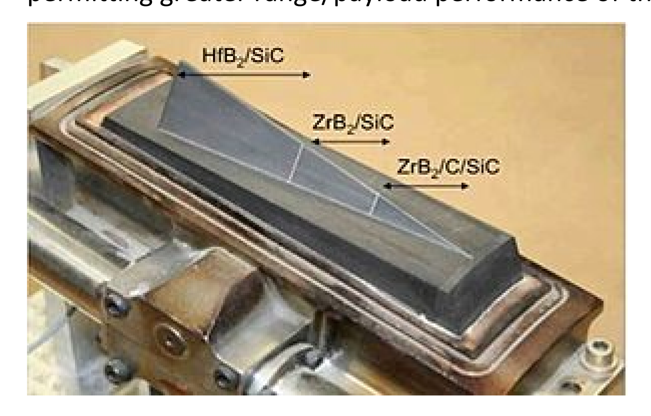


Figure 73: An UHTC strake composed of three different sections with different UHTC compositions (Handbook of Ceramic Composites)

Other Uses: Silicon-carbide's abrasive qualities, low cost, and durability are useful in lapidary work as well as such abrasive machining functions as sandblasting, honing, water-jet cutting, and grinding. Silicon-carbide is used in composite armor as well as in the ceramic plating of bullet-proof vests. Recently developed body armor manufactured from small overlapping silicon-carbide ceramic plates affords the wearer increased flexibility and is resistant to rounds fired from an AK-47.

Ceramic composites that have been reinforced with silicon-carbide are used as thrust vector control flaps in some military jet engines. Silicon-carbide is an important component of light emitting diodes (LED). Its low thermal expansion coefficient, high hardness, and thermal conductive properties are used in manufacturing mirrors for astronomical telescopes. The compound is also used in some automotive as well as gas turbine engines, furnaces, and passive solar energy panels. It is found in furnace tiles, welding cups, and in industrial applications that perform at high temperatures.

The Ultra High Temperature Ceramics that use diborides of hafnium and zirconium are of particular interest to the aerospace industry for sharp leading edge applications which require chemical and structural stability at extremely high operating temperatures. Sustained hypersonic flight is limited by materials due to high heat flux over small areas; high temperature, oxidation, erosion and; very high temperature gradients within the material. The use of UHTCs to conduct energy through the material and radiate it through cooler surfaces is an alternative method to manage heat for hypersonic control surfaces.

Appearance (as manufactured): Ceramic composite materials produced as components of rockets, for example RV antenna windows, are reinforced with ceramic filament to prevent failure as a result of heat-caused stress. The three-dimensional silica-silica used to make antenna windows may have a textile pattern on all surfaces. To prevent against moisture, this material is often protected with a clear coating. Ceramics reinforced by silicon-carbide will exhibit the same surface pattern but the color is black or dark gray. These ceramic substances are much harder than other composites and possess a surface pattern that reflects their textile reinforcement. Size ranges from 1 mm discs to 50 cm cubes that can subsequently be cut or tooled to the desired shape.

Appearance (as packaged): Silicon-carbide is a brittle compound, and thus shock-absorbent substances are used to pack silicon-carbide composites. Sealed bags or other plastics are used to prevent exposure to moisture during shipping. Larger shipments often contain desiccants. Sealed bags are sometimes filled with dry nitrogen to provide additional protection against water absorption.

6.C.7. Materials for the fabrication of missile components in the systems specified in 1.A., 19.A.1. or 19.A.2., as follows:

a. Tungsten and alloys in particulate form with a tungsten content of 97% by weight or more and a particle size of 50 x 10^{-6} m (50 µm) or less;

b. Molybdenum and alloys in particulate form with a molybdenum content of 97% by weight or more and a particle size of 50 x 10^{-6} m (50 µm) or less;

c. Tungsten materials in the solid form having all of the following:

1. Any of the following material compositions:
    - i. Tungsten and alloys containing 97% by weight or more of tungsten;
    - ii. Copper infiltrated tungsten containing 80% by weight or more of tungsten; or
    - iii. Silver infiltrated tungsten containing 80% by weight or more of tungsten; and

2. Able to be machined to any of the following products:
    - i. Cylinders having a diameter of 120 mm or greater and a length of 50 mm or greater;
    - ii. Tubes having an inner diameter of 65 mm or greater and a wall thickness of 25 mm or greater and a length of 50 mm or greater; or
    - iii. Blocks having a size of 120 mm x 120 mm x 50 mm or greater.

- Germany
- Japan
- Russian Federation
- United States

Global Production



Nature and Purpose: Tungsten and molybdenum are elements that belong to a class of refractory metals. Common properties of these refractory metals are melting points above 2,000 °C, relatively high density, chemical inertness, and resistance to creep deformation in high temperature environments. Due to the high melting point of these materials powder metallurgy processes are the preferred fabrication method.

Tungsten and alloys containing tungsten in powder form provide unique properties for producing missile components. The very high melting point of tungsten (3,422 °C), the ability to control the porosity of the part and its resistance to self-diffusion make it ideal for areas in the rocket nozzle that must operate in extreme conditions such as throat inserts. Molybdenum and alloys containing molybdenum in powder form is often used where the environment permits (its melting point is 2,623 °C) since it is less expensive and lighter than tungsten.

Tungsten in solid form can be infiltrated with copper or silver. The resulting composite material is lighter than pure tungsten, is more easily machined and resists thermal shock breakdown due to increased thermal conductivity provided by the infiltrated material.

Typical Missile-Related Uses: Tungsten and molybdenum alloys are used in missile systems for vector control vanes, nozzle and throat inserts, plume deflector shields and RV nose tips.

Other Uses: Tungsten powder is used in metal evaporation work, glass-to-metal seals, electrical contacts, and as an alloying element for steel. Tungsten-carbide coated cutting tools are critical for metal working, mining, and petroleum industries. Copper infiltrated tungsten is also used for welding electrodes, high voltage electrical contacts and some applications for Electrical Discharge Machining (EDM) electrodes requiring sharper detail and superior surface finish. Molybdenum is primarily used as an alloying element for steel production. Other applications include heating elements for furnaces and as an additive for high temperature lubricants.

Appearance (as manufactured): Tungsten, molybdenum, and their alloys as spherical or atomized particles look like many other powder metallurgy products. The particles have a metallic sheen and flow freely because of their spherical shape. Tungsten in solid form is a silvery-white lustrous metal that tarnishes in air forming a protective oxide coating.

Appearance (as packaged): These materials, in particulate form, are packaged in sealed containers or drums to minimize contact with air and oxidation of the surface of the particles. The containers feel heavy for their size and are secured to a pallet or container to prevent movement.

6.C.8 Maraging steels, usable in the systems specifed in 1.A. or 19.A.1., having all of the following:

a. Having an ultimate tensile strength, measured at 20ºC, equal to or greater than:

1. 0.9 GPa in the solution annealed stage; or

2. 1.5 GPa in the precipitation hardened stage; and

b. Any of the following forms:

1. Sheet, plate or tubing with a wall or plate thickness equal to or less than 5.0 mm; or

2. Tubular forms with a wall thickness equal to or less than 50 mm and having an inner diameter equal to or greater than 270 mm.

Technical Note:

Maraging steels are iron alloys:

a. Generally characterised by high nickel, very low carbon content and use substitutional elements or precipitates to produce strengthening and age-hardening of the alloy; and

b. Subjected to heat treatment cycles to facilitate the martensitic transformation process (solution annealed stage) and subsequently age hardened (precipitation hardening stage).

•Austria	•China
•France	•Georgia
•Germany	•India
•Iran	•Israel
•Japan	•Russian Federation
•South Africa	•Republic of Korea
•Sweden	•Switzerland
•United Kingdom	•United States

Global Production



Nature and Purpose: Maraging steel is noted for its high ultimate tensile strength and good fracture toughness while maintaining its machinability, malleability and weldability. Maraging steels differ from conventional steels in that they use precipitation of intermetallic compounds instead of carbon to achieve a desired strength. Typical formulations of maraging steel have a relatively high nickel content (18% or higher). The intermetallic compounds come from the addition of cobalt, molybdenum and titanium. The carbon content (less than 0.03%) is maintained for all grades of maraging steel.

Typical Missile-Related Uses: The forms controlled by the MTCR (sheets, plates, and tubes) are generally used to make solid rocket motor cases, propellant tanks, and interstage components.

Other Uses: These steels are used in special aircraft parts, submarine hulls, fencing blades, pipes, and reactors in the chemical and nuclear industries.

Appearance (as manufactured): Maraging steel has a lustrous gray color when clean and freshly prepared.

If the metal has been subjected to an aging treatment to improve strength, it may have a dark oxide layer on the surface. This dark layer may also indicate that the maraging steel has been subjected to a controlled degree of oxidation in order to improve corrosion resistance during service.

Appearance (as packaged): Maraging steel is often shipped in the low-strength, non-heat-treated condition so that it can be formed into the desired shape by the end user. It is bundled and shipped much like stainless steel, which it closely resembles. Sheets and plates are stacked and secured to a pallet. Tubes are bundled and secured to a pallet as well. Both may be covered with plastic sheet and/or crated to protect the materials from the shipping environment.

6.C.9. Titanium-stabilized duplex stainless steel (Ti-DSS) usable in the systems specified in 1.A. or 19.A.1. and having all of the following:

a. Having all of the following characteristics:

1. Containing 17.0 - 23.0 weight percent chromium and 4.5 - 7.0 weight percent nickel;
2. Having a titanium content of greater than 0.10 weight percent; and
3. A ferritic-austenitic microstructure (also referred to as a two-phase microstructure) of which at least 10% is austenite by volume (according to ASTM E-1181-87 or national equivalents); and

b. Any of the following forms:

1. Ingots or bars having a size of 100 mm or more in each dimension;
2. Sheets having a width of 600 mm or more and a thickness of 3 mm or less; or
3. Tubes having an outer diameter of 600 mm or more and a wall thickness of 3 mm or less.

- Japan
- Russian Federation
- Republic of Korea
- United Kingdom
- United States

Global Production



Nature and Purpose: Titanium Stabilized Duplex Stainless Steel (Ti-DSS) is a special alloy of stainless steel noted for its ease of welding and resistance to corrosive liquid propellant oxidizers. Typical formulations for Ti-DSS range from 17% to 23% by weight of chromium and 4.5% to 7.0% by weight of nickel, and such steel contains traces of titanium which, compared to other stainless steels, makes Ti-DSS particularly resistant to oxidizers such as Inhibited Red Fuming Nitric Acid (IRFNA). Additionally, Ti-DSS is a preferred material for liquid propellant missile applications because it is easily welded using common welding technology and, unlike other forms of stainless steel, does not require heat treatment after welding.

Typical Missile-Related Uses: Ingots or bars, sheets, and tubes meeting the MTCR-criteria are of sufficient size to be used to manufacture liquid propellant tanks and rocket engine plumbing.

Other Uses: There are very few known commercial uses for Ti-DSS. Although usable for many stainless steel applications, Ti-DSS is very hard, making it difficult to form into sheets or tubing. Machining or shaping this material is generally too expensive for common commercial applications. Additionally, although it is especially resistant to IRFNA, a common missile oxidizer, it does not perform well when exposed to other similarly corrosive materials such as chemical fertilizers.

Appearance (as manufactured): Ti-DSS is virtually identical in appearance to other stainless steels. It has a very fine grain, which usually requires a magnifying glass or microscope to view.

Appearance (as packaged): Ti-DSS is generally bundled and shipped much like other stainless steels. Sheets and ingots or bars are often stacked and secured to a pallet. Tubes are usually bundled and secured to a pallet as well. Both may be covered with plastic sheet and/or crated to protect the materials from the shipping environment.

6.D. Software

6.D.1. "Software" specially designed or modified for the operation or maintenance of equipment specified in 6.B.1.

- France
- India
- Japan
- Russian Federation
- Switzerland
- United States
- Germany
- Italy
- Netherlands
- Sweden
- United Kingdom



Nature and Purpose: Software for composite and fiber production equipment is used in CNC devices that control the motion of filament-winding, fiber/tow placement machines, and tape-laying machines. Most of these machines provide simulation software that allows the machine motion to be optimized off-line. Other software in this category is used to control multi-directional, multidimensional weaving and interlacing machines used to manufacture complex composite structures.

Method of Operation: The software is specifically configured to operate in CNCs connected to filament winding machines, fiber/tow placement machines, and tape-laying machines. Multi-directional, multidimensional weaving and interlacing machines have programmed patterns stored in databases that can be modified for individual components.

Typical Missile-Related Uses: The software can be used to produce motor cases, fins, nozzles, RV nose tips, airframes, and other parts and components for rockets and UAVs.

Other Uses: The software can be modified to produce liquid natural gas storage tanks, hot water tanks, compressed natural gas tanks, golf club shafts, tennis racquets, fishing rods, and commercial and military aircraft parts.

Appearance (as manufactured): Magnetic tape, floppy disks, removable hard disks, USB flash drives, compact discs and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, USB flash drives, compact discs and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network.

6.D.2. "Software" specially designed or modified for the equipment specified in 6.B.3., 6.B.4. or 6.B.5.

- China
- France
- India
- Japan
- South Africa
- United Kingdom
- Denmark
- Germany
- Israel
- Russian Federation
- Sweden
- United States

Global Production



Nature and Purpose: Software used in the isostatic press control computer operates the press and monitors the pressure and water coolant temperature. CVD equipment uses software to control the process of heating and supplying the deposition gasses to the porous carbon preform. Process control software is used to operate the high-temperature pyrolysis ovens and to monitor and control the processes used to produce objects such as rocket nozzles and RV nose tips.

Method of Operation: Software used in the isostatic press control computer accepts operator input specifying pressure and time. The software activates the press and controls the operating pressure over time. It monitors the cooling-water temperature and oven heat to insure the system operates in the appropriate and safe zone for the item. The CVD process operator uses a computer loaded with the appropriate process control software to set the furnace temperature, to set the infusion gas pressure and timing and to monitor the cooling-water temperature and other instrumentation and sensor outputs. Precise temperature control over a relatively long time frame is critical to producing carbon-carbon rocket nozzles and nose tips. Process control software used to produce structural

composite materials controls the pyrolysis oven temperatures and pressures over a user-determined number of cycles.

Typical Missile-Related Uses: The software used to control the densification and pyrolysis processes are used to manufacture highly temperature-resistant and lightweight missile components like rocket motor nozzles and RV nose tips.

Other Uses: Isostatic press control software is used in processes to diffusion bond similar and dissimilar materials. CVD process control software is used to produce coated optics, cutting tools, medical instruments, and manufacture semiconductors. Software that controls densification and pyrolysis processes is also used to diffusion bond metals and for treating metal components.

Appearance (as manufactured): Typically, process control software is a computer program stored on printed, optical, magnetic or other media. Any common media including magnetic tape, floppy disks, removable hard disks, USB flash drives, compact discs and documents can contain this software.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, USB flash drives, compact discs and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the soft copies of the documentation, is capable of being electronically transmitted over a computer network.

6.E. Technology

6.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment, materials or "software" specified in 6.A., 6.B., 6.C. or 6.D.

6.E.2. "Technical data" (including processing conditions) and procedures for the regulation of termperature, pressures or atmosphere in autoclaves or hydroclaves when used for the production of composites or partially processed composites, usable for equipment or materials specified in 6.A. or 6.C.

- The autoclave or hydroclave equipment is produced in most industrial countries because it is used in common manufacturing processes. Although general knowledge of these processes is widely known, data on processes for specific applications are proprietary.

Global Production

Nature and Purpose: Technology for the production of structural components, pyrolytic deposition and densification, and structural materials as outlined in 6.A, 6.B, and 6.C is controlled by the Annex. This would include the knowledge to properly select the raw materials (fiber, epoxy or resin system, hardeners) along with the methods (process and assembly instructions) to produce composite and resaturated pyrolised components along with the proper operation and

maintenance of the equipment used. Training on the use of software as defined in 6.D of the Annex and the associated documentation would also be controlled.

Process control data are used to manage the processing of composites or partially processed composites into useful components. The technical data of interest with respect to autoclaves and hydroclaves generally concern processing parameters and procedures, tooling and preparation for cure and cure control. Because the precise process settings for temperature, pressure and duration have a critical effect on the strength, impact resistance and flexural modulus of the parts produced, manufacturers have developed proprietary processes. They rarely release the information for production of specific parts. Processing conditions, debulking periods and related procedures are usually individually tailored for the specific part geometry and material/resin system employed.

Method of Operation: These data are used as guidance in making or partially processing specific, composite parts in autoclaves and hydroclaves. Cure control can be carried out by a human operator, but it is more commonly carried out by computer due to the length of time required for the process. The latter may be based on an equipment manufacturer's prescribed process cycle or on a combination of analytical process models, sensors in or near the part being processed, and process knowledge built into the system.

Typical Missile-Related Uses: These data are part of the instructions for preparing the preform or composite for use as highly heat-tolerant and ablative components such as RV nose tips and rocket motor nozzles.

Other Uses: Similar processes and procedures are used to make the materials for commercial applications of composite technology, from boat hulls to golf clubs.

Appearance (as manufactured): In general, technical data can take the form of blueprints, plans, diagrams, models, formulae, engineering designs and specifications, and manuals and instructions written or recorded on other media or devices such as disk, tape, USB drives, and read-only memories. These data are usually provided in handbooks and graphs as part of either the autoclave or hydroclave manufacturer's documentation, or as a part of the resin manufacturer's recommendations. The manufacturer's documentation refers to each of the subcomponents and compiles specifications and instruction manuals for each of them. These components include items such as solid-state controllers or computers for controlling and monitoring temperature and pressure during the cure operation.

Appearance (as packaged): The data accompanying the equipment and containing the cure information are typically placed in loose-leaf books or a collated set of instructions. Documentation has a report format and accompanies new equipment. Data supplied by manufacturers of resin or prepreg are on data sheets and accompany the raw resin or prepreg material.

6.E.3. "Technology" for producing pyrolytically derived materials formed on a mould, mandrel or other substrate from precursor gases which decompose in the 1,300 ^{0}C to 2,900 ^{0}C temperature range at pressures of 130 Pa (1 mm Hg) to 20 kPa (150 mm Hg) including "technology" for the composition of precursor gases, flow-rates, and process control schedules and parameters.

Nature and Purpose: Pyrolytic deposition is a high-temperature process used to deposit a thin, dense coating of metal, ceramic, or carbon onto a substrate (mold or mandrel) to form a part. It also can be used to coat another material to achieve strong adhesion and bonding between the coating material and the underlying surface. The purpose of these processes is to improve the ability of the coated or densified items to survive the extreme environments in which critical rocket system parts operate.

The general procedures and methods used to create pyrolytically derived materials and their precursor gasses are widely known. However, specific formulae, processes and equipment settings are usually empirically derived and considered proprietary trade secrets by industry. Controlled data (technology) may take the form of technical assistance including instruction, skills, training, working knowledge, procurement assistance and consulting services. Technology may take the physical form of blueprints, plans, diagrams, models, formulae, engineering designs and specifications, and manuals and instructions written or recorded on other media or devices such as disk, tape, USB drives, CD-ROM and DVD.

Method of Operation: The technology for pyrolytic carbon deposition is found in primarily small laboratory environments. There is no known large-scale industrial production by pyrolytic carbon deposition. The technology is not readily shared nor exported. The technology for metal or ceramic deposition is more prevalent and could be acquired by a country by several means. A country may gain the technology through instruction provided by a person experienced in one of more of these controlled subjects who acts as a trainer in a classroom on or near the production site. A country may receive technical assistance from one or more consulting services that specialize in a particular production skill or in the procurement of technical machinery, tools and materials. Finally, a country may receive technical assistance by sending students to other countries possessing the technology to attend training and practice the skills necessary to build and operate the required systems. Any manuals and materials received from this assistance may qualify as technical data.

Typical Missile-Related Uses: This technology is used to build missile heat shields and coating nozzle throat inserts.

Other Uses: Some "technology" may have functionality in the military or commercial aircraft industry, in the manufacture of dies and forming tools that shape semi-molten glass as well as heater elements, sputtering targets, and thermal insulators. This technology may also be used by specialty glass manufacturers.

Appearance (as manufactured): N/A.
Appearance (as packaged): N/A.

Category II - Item 7

Reserved for future use

Category II - Item 8

Reserved for future use

Category II - Item 9

Instrumentation, Navigation and Direction Finding

Category II – Item 9: Instrumentation, Navigation and Direction Finding

9.A. Equipment, Assemblies and Components

9.A.1. Integrated flight instrument systems which include gyrostabilisers or automatic pilots, designed or modified for use in the systems specified in 1.A., or 19.A.1. or 19.A.2. and specially designed components therefor.

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Norway
- Russian Federation
- South Africa
- Spain
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: Integrated flight instrument systems use a variety of sensors as well as inertial instruments (accelerometers and gyroscopes) to track the flight path of rocket systems and UAVs. By collecting and using more data than purely inertial guidance sets, these systems are highly accurate, while the additional sensor data may allow the use of less expensive inertial instruments with large time dependent errors without a reduction in overall system accuracy. Manufacturers have used a variety of names for integrated flight instrument systems, such as integrated navigation systems, and such systems with other names may also be controlled under 9.A.1.

Method of Operation: Integrated flight instrument systems collect and process in-flight data from active and passive sensors, receivers, and inertial instruments in order to track the missile's flight path. They use one of several hierarchical or voting schemes to derive the best estimate of position and heading for comparison with the preprogrammed flight path. The results are used to generate signals to steer the vehicle along the intended flight path and to trigger other preprogrammed functions (such as payload release) at their appropriate time.



Figure 74: The main body of a cruise missile's integrated flight instrument system. (Litton Guidance and Control Systems)

Typical Missile-Related Uses: Integrated flight instrument systems are required equipment in UAVs, including cruise missiles.

Other Uses: Integrated flight instrument systems are used in both civilian and military aircraft.

Appearance (as manufactured): Integrated flight instrument systems vary greatly in size and appearance because they are designed for different interior configurations of different vehicles, and use various combinations

of subsystems. Systems designed for cruise missiles or other larger UAVs, can be as large as 0.5 m in length and weigh several kilograms (Figure 74). Others designed for smaller UAVs can be as small as 0.2 m x 0.2 m x 0.1 m, and weigh as little as 1 kg (Figure 75). As with missile guidance systems controlled under 2.A.1.d., most integrated flight instrument systems controlled by 9.A.1. are enclosed in metallic (often aluminum) boxes, which often have removable access panels. In some cases, components of the system may be distributed throughout the missile, with some sensors and antennas located well apart from the computer and inertial measurement unit (IMU).







Figure 75: A selection of inertial navigation systems (INS) designed for UAV applications. *From left*: an autopilot and mission management system for UAVs and other military applications; a fully-integrated INS/GPS system; and a system which has integrated solid-state gyros, accelerometers, magnetometer and GPS receiver. (Rockwell Collins)

Appearance (as packaged): Although integrated flight instrument systems are not as delicate and expensive as some of the more expensive ballistic missile guidance sets, their packaging is usually robust and includes desiccants and air-tight wrappers for protection against moisture. These systems are usually shipped in cushioned containers with labels indicating the need for careful handling.

9.A.2. Gyro-astro compasses and other devices which derive position or orientation by means of automatically tracking celestial bodies or satellites, and specially designed components therefor.

Nature and Purpose: Gyro-astro compasses are precision assemblies of sensitive optical and electro-mechanical equipment used for navigation. They provide an in-flight orientation update and thereby increase the navigational accuracy.

Method of Operation: These devices use an optical sensor to detect a distant point-source of light in a known direction, typically relying on stars, but also making use of satellites travelling in known orbits. The guidance computer compares the expected direction of the star on the current trajectory with its measured direction and sends signals to the flight control system to make any necessary course corrections.

- France
- Germany
- Russian Federation
- United Kingdom
- United States

Global production



Typical Missile-Related Uses: Gyro-astro compasses are used in missiles that fly a portion of their trajectory above the atmosphere.

Other Uses: Gyro-astro compasses are used in space probes and some aircraft as well as on some ships to aid in navigation.

Appearance (as manufactured): Improvements in optical sensor technology have reduced the size and weight of such sensors, and are likely to continue to do so. Although gyro-astro compasses vary considerably in design, the optical sensors, or telescopes, all have a visible optical lens, which may be protected by an automatic shutter or trap door. Many telescopes are gimbal-mounted (i.e., mounted inside one or more pivoting cages) and thus can be automatically pointed to locate an optical reference. A typical unit might measure less than half a meter and weigh less than 10 kg. A photograph of a gyro-astro compass is shown in Figure 76. Compasses without gimbals consist of little more than an optical sensor with precision mounting surfaces, a shutter, and supporting electronics. Their metal cases often measure only 5 cm to 7 cm on a side and weigh approximately 0.5 kg.



Figure 76: A high resolution gyro-astro compass. (Litton Alenia Difesa)

Appearance (as packaged): Because gyro-astro compasses are delicate mechanisms, they are usually packed in robust shipping containers that prevent damage from moisture and mild shock. Shipping containers usually have warning labels indicating that they contain costly assemblies of sensitive optical, electrical, or mechanical equipment.

9.A.3. Linear accelerometers, designed for use in inertial navigation systems or in guidance systems of all types, usable in the systems specified in 1.A., 19.A.1. or 19.A.2., having all of the following characteristics, and specially designed components therefor:

a. 'Scale factor' 'repeatability' less (better) than 1250 ppm; and
b. 'Bias' 'repeatability' less (better) than 1250 micro g.

Note:
Item 9.A.3. does not control accelerometers specially designed and developed as Measurement While Drilling (MWD) sensors for use in downhole well service operations.

Technical Notes:
1. 'Bias' is defined as the accelerometer output when no acceleration is applied.
2. 'Scale factor' is defined as the ratio of change in output to a change in the input.
3. The measurement of 'bias' and 'scale factor' refers to one sigma standard deviation with respect to a fixed calibration over a period of one year.
4. 'Repeatability' is defined according to IEEE Standard for Inertial Sensor Terminology 528-2001 in the Definitions section paragraph 2.214 titles repeatability (gyro, accelerometer) as follows: 'The closeness of agreement among repeated measurements of the same variable under the same operating conditions when changes in conditions or non-operating periods occur between measurements'.

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- North Korea
- Norway
- Pakistan
- Russian Federation
- South Africa
- Sweden
- United Kingdom
- United States

Global production



Nature and Purpose: Accelerometers are sensitive pieces of electro-mechanical equipment used in measuring acceleration, which is the rate of change of speed in a given direction. Acceleration is integrated once to provide velocity and integrated again to provide distance traveled from the point of origin or launch.

Missile accuracy is directly dependent on the quality of the missile's accelerometers and gyros; missiles that fly for a long time without external updates require high quality accelerometers. Missiles that use sensor systems like Global Navigation Satellite Systems (GNSS) receivers, stellar fixes, or terrain-matching sensors to make mid-flight corrections can use lower quality accelerometers (Figure 77). Much of the cost of high quality inertial-grade accelerometers results from the extensive calibration testing that must be performed on each unit.

Method of Operation: Accelerometers receive electrical power, sense acceleration, and provide



Figure 77: This accelerometer is used in many commercial and military strapdown inertial navigation systems. (Honeywell)

measurement information as an electric signal. Information from the accelerometer, along with information on time, local gravity, orientation, and possibly other measurements, allows vehicle speed, heading, and position to be estimated by the guidance set or integrated flight instrument system. Several different types of accelerometers exist, each with its own method of operation.

Many pendulous accelerometers (often referred to as force balance, force to balance, or force rebalance accelerometers) use a small weight on a flexible hinge that is supported against the forces of gravity and acceleration by a magnetic field. Numerous variations of this design exist, but the principles are much the same. The small weight is held in a null position by an electromagnet. As the acceleration changes, the weight moves, and control circuitry changes the current in the electromagnet to bring the weight back to the null position. The amount of current required for this repositioning, or rebalancing, is proportional to the acceleration.

A common pendulous accelerometer used in navigation and guidance systems is known as a Q-Flex (quartz flexure) accelerometer. The one-piece hinge and pendulum structure is made from fused quartz, a very stable and non-conducting material. Applied acceleration produces a torque on the quartz proof mass assembly. Displacement sensed by a detector produces a proportional output voltage. This output is amplified and conditioned, then fed to a torquer coil fixed to the proof mass. The current through the coil, in the permanent magnetic field, develops a restoring torque equal and opposite to the applied acceleration. The same current passes through an external load resistor generating an output voltage proportional to applied acceleration.

A spinning mass gyroscope with an unbalanced mass added along its spin axis can be used as an accelerometer. The gyroscope revolves about a pivot perpendicular to its axis of spin at a rate proportionate to acceleration including gravity. The sum of these revolutions serves as a mechanical integration of acceleration to provide an output proportionate to velocity rather than acceleration. Accelerometers of this type are known as pendulous integrating gyroscopic accelerometers (PIGAs) (Figure 78). PIGAs can be very expensive and have been used in some of the most accurate long-range ballistic missile systems.

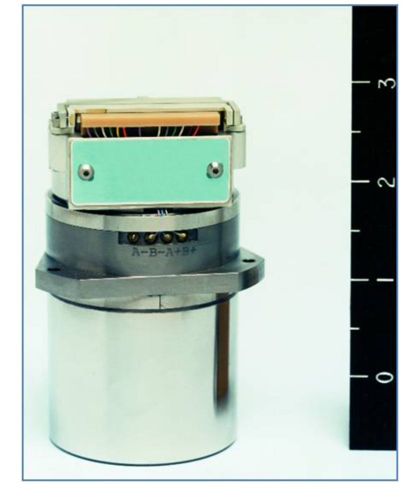


Figure 78: A pendulous integrating gyro accelerometer (PIGA) next to an inch scale. (The Charles Stark Draper Laboratories, Inc.)

Other accelerometer designs also exist such as vibrating element accelerometers that vary the tension and frequency of a vibrating element. Chip accelerometers use a flexible portion of the microcircuit

semiconductor to vary electrical resistance and produce an electrical output (Figure 79). Accelerometers of this type are at the lower end of the performance range, but design efforts will continue because of the potential for substantial cost reduction. Such modern accelerometers are already used in IMUs requiring a lower degree of accuracy.

Typical Missile-Related Uses: Accelerometers are used in missile guidance sets or integrated flight instrument systems. Typically, three accelerometers mounted perpendicular to each other provide all the acceleration measurement information necessary for inertial navigation. They can be installed in a gimbal structure (see 2.A.1.d.), mounted in a floating ball, or affixed (strapped down) to the missile frame. Combined with gyroscopes, they make up an IMU or inertial sensor assembly (ISA). Depending upon mission requirements, some UAVs, including cruise missiles, can make do with only one or two accelerometers.

Other Uses: Accelerometers are used in both civilian and military aircraft and space systems, in oil well drilling stress testing, as inertial navigators in cars and other land vehicles, and in electronic equipment, gravity meters, robotics, mobile phones, and carnival rides (roller coasters). However, most of these uses do not require the high stability and highly calibrated accuracy of inertial-grade accelerometers.

Appearance (as manufactured): Accelerometers vary greatly in appearance because many designs exist. They are usually cylindrical, metallic, and shiny from precision machining. The larger accelerometers used in ballistic missiles are several centimeters in length and can weigh up to several kilograms. Those used in UAVs, including cruise missiles, are smaller and lighter; they may measure only a few centimeters on a side and weigh less than a kilogram. Many accelerometers of MTCR concern have high quality electrical connections and precision mounting surfaces for accurate alignment. Many accelerometers are factory-sealed instruments, not usually disassembled or even opened for service by any customer. The model and serial number on the exterior of the accelerometer should appear on the associated documentation, which contains information about accuracy.

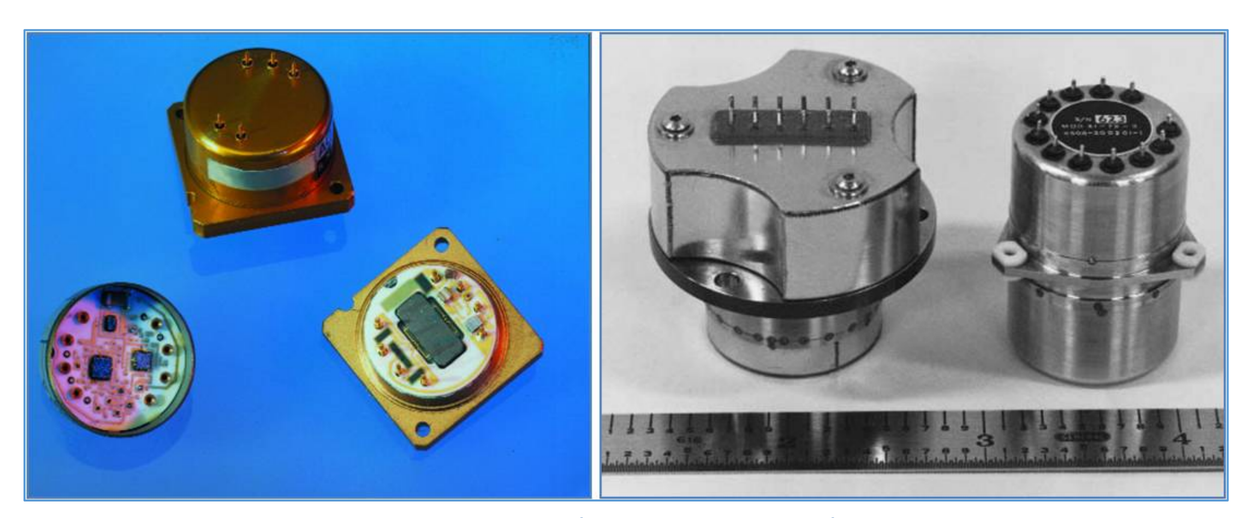


Figure 79: *Left*: An integrated circuit accelerometer. (Litton Sextant Avionique) *Right*: Two force-rebalance accelerometers that can be built with any of a wide range of performance capabilities. (Lockheed Martin Federal Systems)

Distinguishing MTCR-controlled from other accelerometers simply by visual inspection can be difficult because, although different models of an accelerometer have different performance capabilities, they may look identical. Relevant information unique to each model and serial-numbered accelerometer can be derived from the associated documentation (often called a calibration sheet or cal-data), including the g-threshold and linearity error. A major factor that makes an accelerometer accurate enough for use in sophisticated missile guidance sets is the exhaustive testing needed to compile the calibration data. Thus, the detail and amount of the calibration and error modeling data associated with each accelerometer are key indicators for determining the missile-related use of an accelerometer.

Appearance (as packaged): Because they are designed to be sensitive to acceleration, precision accelerometers are vulnerable to damage from relatively minor impact. They are usually protected from physical shock in small, high quality packages with thick, contour-fitted foam lining much like a package for a fine pocket watch. For shipping, one or more of these special boxes are packed in yet another box or other container with cushioned lining of some sort. The documentation on the accuracy of each model and serial-numbered accelerometer is usually contained in its package.

9.A.4. All types of gyros usable in the systems specified in 1.A., 19.A.1. or 19.A.2., with a rated 'drift rate' 'stability' of less than 0.5 degrees (1 sigma or rms) per hour in a 1 g environment, and specially designed components therefor.

Technical Notes:
1. Drift rate is defined as the component of gyro output that is functionally independent of input rotation and is expressed as an angular rate. (IEEE STD 528-2001 paragraph 2.56)
2. Stability is defined as a measure of the ability of a specific mechanism or performance coefficient to remain invariant when continuously exposed to a fixed operating condition. (This definition does not refer to dynamic or servo stability) (IEEE STD 528-2001 paragraph 2.247)

- Austria
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- North Korea
- Pakistan
- Russian Federation
- South Africa
- Sweden
- United Kingdom
- United States

Global production



Nature and Purpose: Gyroscopes, or gyros, are sensitive pieces of electro-mechanical or electro-optical equipment that measure rotation about one or more sensitive axis. Gyroscopes are usually mounted with accelerometers in the guidance set or integrated flight instrument system. They measure any change in the angular orientation of the accelerometers, so that the direction of the accelerometer measurements is known. One of the most important performance parameters is drift rate stability, usually measured in fractions of a degree per hour. This determines how quickly the gyro loses knowledge of its orientation. For gyros used in strapdown guidance systems, the stability of the scale factor – the factor relating the sensed rotation rate or

angle and the gyro output signal – is also critical.

Missile accuracy is directly dependent on the quality of the missile's accelerometers and gyros; missiles that fly for a long time without external updates require high quality gyros. Missiles that use sensor systems like Global Navigation Satellite Systems (GNSS) receivers, stellar fixes, or terrain-matching sensors to make mid-flight corrections can use lower quality gyros. Much of the cost of high quality inertial-grade gyros results from the extensive testing that must be performed on each unit.

Method of Operation: Gyros sense angular shifts (changes in orientation) and provide measurement information, as some form of electric signal. The orientation information from the gyros, along with information on time, local gravity, acceleration, and possibly other measurements, allows vehicle speed, heading, and position to be estimated by the guidance set or integrated flight instrument system. Several different types of gyros exist, each with its own method of operation. Most inertially guided missiles use either spinning mass gyros or electro-optical gyros.

Spinning mass gyros contain a spinning disk and operate on the gyroscopic principle whereby a proportionate measurable torque is generated perpendicular to the angular disturbance. There are two common types of spinning mass gyros. Single degree-of-freedom (SDF) gyros sense rotation about only one axis, while two degree-of-freedom (TDF) gyros sense rotation about two axes. Since missile guidance systems usually require orientation knowledge for all three axes, three SDF gyros are required, but only two TDF gyros (one axis will be redundant).

An SDF gyro has the spinning mass suspended cross-axis inside a cylinder that floats inside yet another slightly larger cylinder fixed to the guidance platform. Many designs float the inner cylinder in a liquid while others suspend it with gaseous flow. Rotations of the floated inner cylinder are related to input orientation changes by the gyroscopic effect of the spinning mass. Measurement of those rotations or measurement of the force needed to prevent those rotations is the output of the SDF gyro.

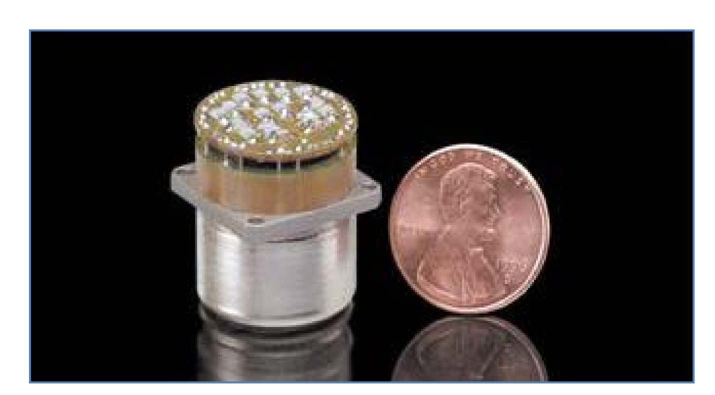


Figure 80: This dynamically tuned gyro (DTG) is used in a variety of military applications, including in inertial measurement units (IMUs) and tactical missile guidance. (Northrop Grumman)

The most commonly used TDF gyro is the dynamically tuned gyro (DTG) (Figure 80). It uses no floatation fluid, so it is sometimes referred to as a "dry" tuned gyro. A DTG has the spinning mass suspended on a complex gimbaled flex-hinge assembly, essentially an ultra-precision universal joint. The complex hinge assembly is tuned so its error torques cancel at one specific speed, often in excess of 10,000 rpm. DTGs need very good speed regulation to operate reliably at the tuned rpm. Older types of TDF gyros consist of a series of mechanical gimbals that isolate the spinning rotor from the case. The angular position of the spinning mass with respect to the case is used

to measure the platform's orientation changes.

Electro-optical gyros generate counter-rotating beams of laser light around a closed path to form an interference pattern that is sensed by a detector. When rotation about an axis not in the plane of the loop occurs, the difference in the effective lengths of the respective paths creates a relative shift of the interference pattern. This shift (known as the Sagnac effect) is observed by the detector, which provides an output proportional to the rotation of the gyro.

There are two common types of optical gyros, the ring laser gyro (RLG) and the fiber optic gyro (FOG), and there are several variations of each. RLGs create their counter-rotating beams of laser light inside gas tubes that are cavities configured in a closed polygonal path, often triangular, but sometimes four or five sided. These cavities are made in glass with a near-zero thermal expansion for higher accuracy. FOGs use long spools of fiber optic cable to carry the counter-rotating beams.

An important difference between RLGs and FOGs is that the spool of fiber optic cable gives the FOG a much longer optical path length and, at least theoretically, better accuracy. In practice, however, this improvement is offset by imperfections in the fiber optic cable and cable interfaces.

FOGs are designed as single-axis gyros so most missiles that use them will need three to track rotations about all three axes; the same is true of single-ring RLGs. Sometimes multi-axis RLGs are used that contain three or more rings in a single block of glass; only one such unit would be required in a guidance set.

Other types of gyros include the hemispherical resonating gyro, which establishes and monitors a standing vibration wave in a hemispherical cup (somewhat like a small wineglass). There are also designs like small tuning forks that operate by a method that involves Coriolis force. However, any gyro capable of meeting MTCR performance specifications is controlled regardless of its method of operation.

Typical Missile-Related Uses: Gyros are used in a missile's guidance set or integrated flight instrument system to sense changes in accelerometer orientation. Designs may use two, three, or four gyros. They usually are mounted perpendicular to each other in order to provide angular measurement information about all three axes. They can be used in a gimbal structure (see Item 2.A.1.d.), mounted in a floating ball, or affixed to a block which is in turn affixed to the missile airframe in a strapdown configuration. Combined with accelerometers, they make up the IMU or ISA.

Other Uses: Gyros are used in non-missile guidance sets, integrated flight instrument systems, gyrostabilizers, automatic pilots, and in navigational equipment. Military applications include artillery, tanks, ships, and aircraft. Commercial applications include ships, aircraft, and oil drilling. In most non-missile applications, gyros can be smaller, cheaper, and less complex because operating environments and accuracy requirements are usually less demanding.



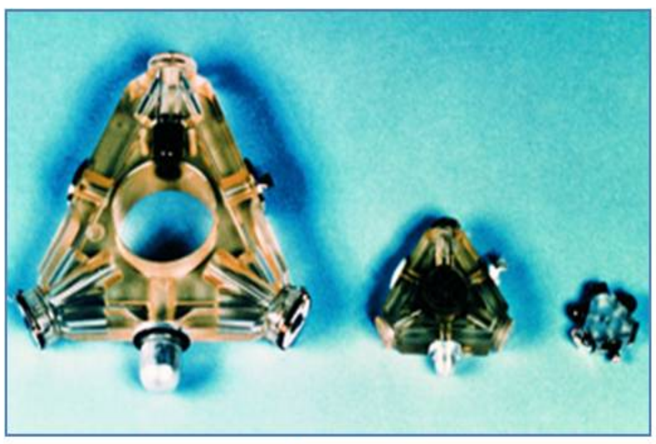
Figure 83: A FOG (left), an RLG (center), and an accelerometer (right). (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))



Figure 82: A dynamically tuned gyro (DTG). (The Charles Stark Draper Laboratories, Inc.)



Figure 81: A vibrating structure gyro. (British Aerospace Ltd.)



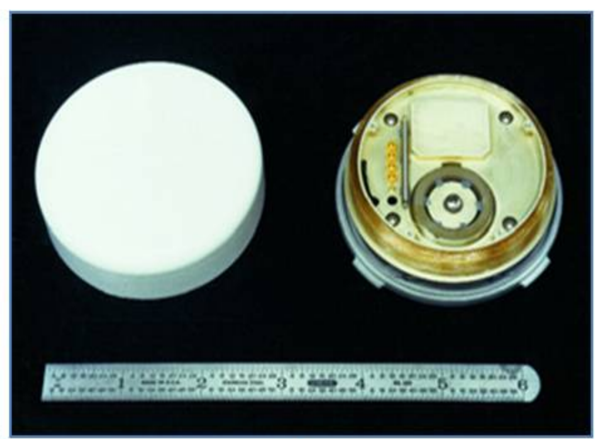




Figure 84: *Top left*: three exposed ring laser gyros without their associated electronics. (Honeywell) *Top right*: a fiber optic gyro with its top removed. (Honeywell) *Bottom*: a fiber optic, rate sensing gyro. It is 2 cm x 6.5 cm x 8 cm. (LITEF)

Appearance (as manufactured): Modern SDF gyros can be 5 cm to 8 cm in diameter and 8 cm to 12 cm long, and weigh up to 1 kg. DTGs are usually cylindrical with diameters of 4 cm to 6 cm and lengths of 4 cm to 8 cm, and generally weigh less than 1 kg. Older gyros can be somewhat larger, approximately twice the size of newer gyros and weigh several kilograms. Gyros used in UAVs, including cruise missiles, can be much smaller and lighter, perhaps weighing only tens of grams.

Many gyros of MTCR concern have precision mounting surfaces for accurate alignment and high quality electrical connections. Because many designs exist, a gyro's appearance can vary greatly. Spinning mass gyros are usually cylindrical, metallic, heavy for their size, and shiny from precision machining.



Figure 85: A tactical grade inertial measurement unit is a high-performance fiber optic gyro-based motion sensor used in UAV guidance and navigation systems. (KVH)

Individual optical gyros are usually pad-like and mounted in a low profile, sealed box. A three-ring RLG unit will tend to be cubic and between 4 cm and 10 cm on a side. It may weigh between fractions of a kilogram to over a kilogram. Some single-axis designs resemble cylinders with diameters exceeding 20 cm. Some FOG designs are only 2 cm to 4 cm in diameter, contain a fiber several hundred meters long, and weigh fractions of a kilogram.

MTCR-controlled and uncontrolled gyros may look identical. Relevant information unique to each model and serial-numbered gyro can be derived from the associated documentation (calibration sheet or cal-data), including the drift rate stability. As with accelerometers, the exhaustive testing needed to compile this calibration data is a substantial part of what makes a gyro accurate enough for use in a missile guidance set. Thus, the detail and amount of the calibration and error modeling data associated with each gyro are critical to determining the missile-related use of a gyro. The cal-data normally cites a serial number that is visible on the gyro.

Appearance (as packaged): Spinning mass gyros are vulnerable to damage from shock, but optical gyros are fairly rugged. Spinning mass gyros are packed in high quality, cushioned containers. Optical gyros do not need as much cushioning material in the package, but they are still likely to be shipped in high quality packages typical of expensive electronic instruments and sensors.

9.A.5. Accelerometers or gyros of any type, designed for use in inertial navigation systems or in guidance systems of all types, specified to function at acceleration levels greater than 100 g, and specially designed components therefor.

Note:
9.A.5. does not include accelerometers that are designed to measure vibration or shock.

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- North Korea
- Pakistan
- Russian Federation
- United Kingdom
- United States

Global production



Nature and Purpose: Accelerometers and gyros specified to function at acceleration levels greater than 100 g are a special category of accelerometers and gyros, which may include those in Item 9.A.3. and 9.A.4., respectively. These devices produce uninterrupted signals throughout their specified range and are designed to operate under extreme accelerations in excess of 100 g. All such instruments are controlled under this item regardless of performance specifications. Their purpose is to provide inertial instrument data under heavy accelerations like those experienced by re-entry vehicles (RVs) during defense avoidance and re-entry deceleration. These instruments may also be used as part of a fuzing system. No accuracy specifications are included because instruments with significantly lower accuracy can be used due to the relatively short period of operation.

Method of Operation: These inertial instruments operate in much the same way as those covered in Item 9.A.3. and 9.A.4., but they are ruggedized and have a greater operating range (in excess of 100 g).

Typical Missile-Related Uses: These accelerometers can be used as fuzes in RVs. Continuous output accelerometers and gyros are used in the guidance sets that steer maneuvering RVs as they evade defenses or terminally guide themselves to a target. Such accelerometers and gyros are fairly accurate and probably radiation hardened. Continuous output accelerometers rated in excess of 100 g are also used in fuzing and firing mechanisms for cruise missiles with penetrating warheads.

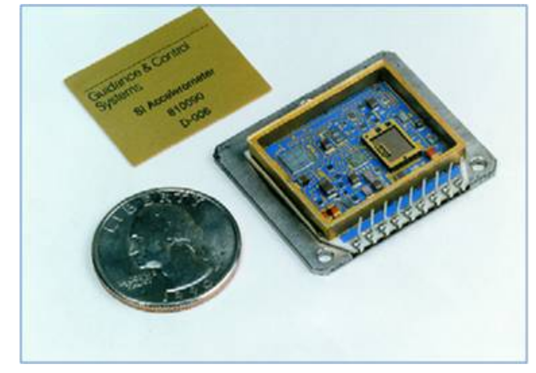


Figure 86: An integrated circuit accelerometer rated at over 100 g. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))

Other Uses: Accelerometers and gyros able to operate in a 100 g environment can be used in guided munitions such as artillery shells. Such accelerometers are also used in laboratories for high-g tests that require continuous output.

Appearance (as manufactured): Accelerometers may look identical to those covered in Item 9.A.3 (Figure 86). Similarly, gyros specified to function at levels greater than 100 g may also be virtually identical in appearance to those covered in Item 9.A.4. They all are usually cylindrical or pad-like with precision mounting flanges and high quality electrical connectors. Because smaller instruments are inherently more g-tolerant, they tend to be smaller than most other accelerometers and gyros. There are even miniature high-g accelerometers integrated into circuit elements.

Appearance (as packaged): Because of their rugged nature, these instruments do not need special handling. They are shipped as small hardware items. The documentation on the operating g range of each model and serial numbered unit is usually contained in its package.

9.A.6: Inertial measurement equipment or systems' using accelerometers specified in 9.A.3. or 9.A.5. or gyros specified in 9.A.4. or 9.A.5., and specially designed components therefor.

Note:
Item 9.A.6. includes:
a. Attitude and Heading Reference Systems (AHRSs);
b. Gyrocompasses;
c. Inertial Measurement Units (IMUs);
d. Inertial Navigation Systems (INSs);
e. Inertial Reference Systems (IRSs);
f. Inertial Reference Units (IRUs).

Technical Note:
"Inertial measurement equipment or systems' specified in Item 9.A.6. incorporate accelerometers or gyros to measure changes in velocity and orientation in order to determine or maintain heading or position without requiring an external reference once aligned.

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Norway
- Pakistan
- Russian Federation
- South Africa
- Spain
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: This MTCR Annex item ensures that any of the accelerometers and gyros controlled in Item 9 remain controlled when they are components of a larger assembly used for navigation and direction finding. Examples of such assemblies include IMUs and complete guidance sets not controlled under 2.A.1.d. Any inertial measurement equipment or system is controlled as Category II under this item if it contains one or more of items 9.A.3., 9.A.4., or 9.A.5.

Typical Missile-Related Uses: This equipment is used in guidance sets and integrated flight instrument systems for ballistic missiles and UAVs, including cruise missiles, as described in Item 2.A.1.d. and 9.A.1.

Other Uses: This equipment can also be used in guidance sets and navigation systems for a whole range of space flight, aviation, gravity mapping, ocean navigation, land navigation, and well drilling uses.

Appearance (as manufactured): The appearance of inertial or other equipment using accelerometers or gyros varies widely. IMUs can be designed to be rigidly mounted in a strapdown configuration. Equipment using accelerometers and gyros may also use optical sensors, Global Navigation Satellite Systems (GNSS) receivers, radar units, horizon sensors, computers and software, and other items, depending on the specific application. The equipment has electrical connectors and mounting surfaces, and may have removable access panels for replacing accelerometers, gyros, or other subelements.

They vary in size and weight depending on application. The IMU shown in Figure 88 is 8 cm in height and just 8.5 cm in diameter, and weighs 750 g.

Appearance (as packaged): Because many accelerometers and gyroscopes are inherently delicate, they are packed in robust shipping containers with cushioning and insulation to prevent damage from shock and moisture. Containers may be wood, metal, or plastic with foam cushioning. The shipping packages are likely to have the cautionary labels usually used on containers of costly assemblies of sensitive electrical or mechanical equipment.





Figure 87: An Inertial Measurement Unit (IMU) utilizes inertial fiber optic gyros (FOGs) and micro-machined accelerometers and is used in space stabilization, missile guidance, UAV guidance and flight control. (Northrop Grumman)

9.A.7. 'Integrated navigation systems', designed or modified for the systems specified in 1.A., 19.A.1. or 19.A.2. and capable of providing a navigational accuracy of 200 m CEP or less.

Technical Note:
An 'integrated navigation system' typically incorporates all of the following components:
a. An inertial measurement device (e.g. an attitude and heading reference system, inertial reference unit, or inertial navigation system);
b. One or more external sensors used to update the position and/or velocity, either periodically or continuously throughout the flight (e.g. satellite navigation receiver, radar altimeter, and/or Doppler radar); and
c. Integration hardware and software.

N.B. For integration "software", see Item 9.D.4.

- Argentina
- Australia
- Brazil
- China
- Denmark
- France
- Germany
- India
- Israel
- Italy
- Japan
- Russian Federation
- South Korea
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: Integrated navigation systems are composed of low-rate update sensors (e.g. Global Positioning Satellite (GPS) receiver, 1-20 Hz) and high-rate propagation sensors (e.g. inertial components, 50-1,000 Hz) to provide a robust position, velocity, and attitude solution to the host platform. The processing software may execute on one of the sensor processors or on an external computing platform.

The update and propagation sensors serve different purposes and have complementary error characteristics. Update sensors such as GNSS, radar altimeters, and Doppler radars produce position and/or velocity solutions by direct measurement and each solution contains an independent error level. Propagation sensors such as inertial components (i.e. accelerometers and gyroscopes) measure incremental changes in velocity and attitude that must be integrated to produce comparisons with the update sensors.

Propagation sensors provide the basis for an attitude solution as they measure attitude changes relative to inertial space. Update sensors are not able to provide an instantaneous attitude measurement.

Various grades of inertial measurement components exist that drive the requirements for the updating sensor rate. Inertial systems for defense applications are typically grouped into tactical, navigation, and marine grades and are differentiated mainly by the quality of their gyroscope components.

Method of Operation: Prior to providing a navigation solution, an inertial platform must be aligned. This is the process by which its attitude estimate is refined to match that of its host platform relative to a local

horizontal navigation frame. It is assumed the mounting angles of the navigation system relative to the host platform are known and do not need to be estimated. Depending on the host platform, this can be accomplished through a static, in-motion, or transfer alignment process.



Figure 88: An internal Inertial Measurement Unit (IMU) and GPS. (Northrop Grumman)

During static alignment, gyrocompassing (i.e. measuring earth rotation rate) is used to find the yaw angle and accelerometers are used to determine pitch and roll angles. With in-motion alignment, errors in the inertially-derived attitude estimate are reduced by comparing the propagated inertial navigation solution with that of the updating system through several measurement epochs. Finally, for a carried weapon, transfer alignment can be used to replicate the host vehicle attitude solution (from its navigation system) to the weapon platform.

Once the inertial attitude solution has converged, accelerometer measurements are mechanized at the inertial propagation rate from their measurement coordinate frame to the local-level navigation frame. The transformed acceleration measurements are then integrated once to produce an incremental velocity change and integrated again to produce an incremental position change within the navigation frame.



Figure 89: An internal Inertial Measurement Unit (IMU) and GPS with laser gyro (inset). (Northrop Grumman)

Typical Missile-Related Uses: Integrated navigation systems are used in UAV systems, including cruise missiles, and some ballistic missile systems. Notable examples include submarine- launched ballistic missiles that incorporate integrated inertial measurement units with stellar sensors or surface-to-surface missiles that utilize GNSS receivers.

Other Uses: Integrated navigation systems serve many purposes outside of missile-based operations. They are commonly used in civilian and military aircraft. They are also used in ground vehicles that operate in urban areas where they may have to deal with GNSS, including GPS, outages or intentional/unintentional RF jamming. An integrated navigation system can rely on the inertial solution between sparsely available GNSS updates.

Remotely piloted vehicles (RPVs) also benefit from integrated navigation systems. They may experience significant dynamic conditions and be exposed to jamming, both of which could cause a satellite navigation receiver to temporarily fail.

Since an integrated navigation system provides a robust attitude solution, aerial platforms that require a precise location and pointing angle of a sensor (e.g. photogrammetry, radar) can have this capability as part of the platform navigation system or as a separately contained unit.

Underwater vehicles with marine-grade inertial components can make use of an integrated navigation system by surfacing periodically to allow GNSS updates. The update period is dependent on the quality of the inertial sensors utilized and the desired navigation solution accuracy over time.


Figure 90: An internal inertial measurement unit (IMU) and GPS. (Honeywell)

Appearance (as manufactured): Integrated navigation system components (e.g. GNSS receiver, inertial components, and integration hardware/processing) are typically mounted in rugged(ized) enclosures with several externally-visible connectors. These connectors provide inputs for power and antennas and outputs to a guidance system or display. The longest enclosure linear dimension is typically just less than one foot (30 cm). It is possible for either the GNSS receiver or inertial measurement unit (IMU) to reside outside the integration hardware/software enclosure depending on the application. These components in multiple forms are shown in Figure 88, Figure 89, and Figure 90.

Appearance (as packaged): Integrated navigation systems would be shipped in metal or plastic crates or in padded cardboard boxes. External cabling and antennas may be included with a shipment depending on the intended platform.

9.A.8. Three axis magnetic heading sensors having all of the following characteristics, and specially designed components therefor:

a. Internal tilt compensation in pitch (+/- 90 degrees) and having roll (+/- 180 degrees) axes.

b. Capable of providing azimuthal accuracy better (less) than 0.5 degrees rms at latitudes of +/- 80 degrees, referenced to local magnetic field; and

c. Designed or modified to be integrated with flight control and navigation systems.

Note:
Flight control and navigation systems in Item 9.A.8. include gyrostabilisers, automatic pilots and inertial navigation systems.

- Finland
- France
- Israel
- Netherlands
- Switzerland
- United Kingdom
- United States

Global production



Nature and Purpose: Three axis magnetic heading sensors measure the earth's magnetic field in three orthogonal components. This field points from the magnetic south pole to the magnetic north pole, is vertical (large "dip" angle) near the magnetic poles, and horizontal (small "dip" angle) near the equator. These sensors derive a heading angle

from the horizontal component of the local magnetic field (Figure 18). Near the poles, an accurate heading measurement is difficult, since the magnetic field has only a small horizontal component.

Once a magnetic heading is calculated, the user or application may prefer the heading to be referenced to true, rather than magnetic, north. This declination correction is calculated as a function of position and time from various global models.



Figure 91: This is a precision stand-alone magnetic heading sensor. (KVH)

Method of Operation: A common type of magnetic sensor utilized for navigational purposes is the magnetoresistive (MR) sensor. This sensor is made up of thin strips of permalloy (NiFe magnetic film) whose electrical resistance varies with a change in applied magnetic field. These sensors have a well-defined axis of sensitivity and are mass produced as an integrated circuit.

Due to ferrous materials present in the host vehicle structure and its associated electrical systems, the measured magnetic field is distorted from that of the true magnetic field. Offsets due to magnetic fields produced by permanent magnets and electrical components are considered "hard-iron" and can be modeled as constant biases. Those that vary with platform orientation are considered "soft-iron." If the platform can be physically rotated, the hard-iron and soft-iron errors can be estimated and stored in calibration tables. Alternatively, some systems utilize a self-generated, variable magnetic field to perform this calibration step in place. Prior to error calibration, it is assumed the mounting angles of the magnetic sensor axes are known relative to the vehicles axes.



Figure 92: This gyro-stabilized magnetic compass module uses three-axis magnetic heading sensors. (Honeywell)

Similar to strapdown inertial measurement units, three axis magnetometer measurements are electronically gimbaled to the local horizontal frame. This is accomplished after measuring vehicle pitch and roll with a three axis accelerometer or with an additional navigation system. Then the heading angle is resolved from the two horizontal magnetic field components.

Gyroscope compensation is also sometimes utilized to allow for a robust heading measurement while the host vehicle is possibly exposed to transient magnetic anomalies.

Typical Missile-Related Uses: Unmanned aerial vehicles (UAVs) can use the heading measurement from magnetic sensors for navigation purposes as they fly between waypoints. Magnetic sensors also have application in laser range finders, antenna alignment, and may also be integrated with Global Navigation Satellite Systems (GNSS) receivers/ inertial navigation systems for missile applications. These sensors serve as an additional measurement source during the update period of a Kalman filter algorithm. The heading estimate may also be directly utilized by the automatic pilot system of a missile guidance system.

Since magnetic sensors make an absolute measurement of orientation, rather than an integrated measurement (e.g. from a gyroscope), they do not suffer from increasingly large drift errors experienced by uncorrected inertial systems. During periods of RF interference, which can deny GNSS updates, magnetic sensor measurements remain useful as they do not require periodic updates.

Other Uses: Magnetic sensors have a number of applications in addition to their utility in missile navigational systems. They are used in ground vehicles to provide the driver with an “8 point” compass reading (e.g. NW, N, NE, etc.). Since ground vehicles typically function close to horizontal, tilt compensation of the sensor measurements may not be required. If magnetic sensors are permanently mounted in a static location, they may be used for vehicle detection and classification as the sensed magnetic fields will vary due to vehicle proximity and ferrous characteristics. Magnetic sensors within personal navigation devices (PNDs) can be used to update map orientation or augment reality features within specific mobile applications as PNDs are rotated.

Appearance (as manufactured): Magnetic sensor components could be mounted as a triad directly on a printed circuit board within a navigation system or may be separated from other electronic components in their own non-ferrous enclosure. A separate enclosure allows the magnetic sensors to be mounted as far away as possible from ferrous materials in the host vehicle. Magnetic sensors are very small in size, with typical dimensions of around 2.5 cm x 2.5 cm x 15 cm. They are also very light, weighing around 15 g to 20 g (Figure 92).

Appearance (as packaged): Magnetic sensor components are shipped in small boxes or crates and are not themselves susceptible to shock damage. However, the tilt compensation components (e.g. accelerometers) could be affected by large shock events, thus requiring the entire system to be padded during shipping.

Note:
Equipment or "software" specified in 9.A. or 9.D. may be exported as part of a manned aircraft, satellite, land vehicle, marine/submarine vessel or geophysical survey equipment or in quantities appropriate for replacement parts of such applications.

9.B. Test and Production Equipment

9.B.1. "Production equipment", and other test, calibration and alignment equipment, other than that described in 9.B.2., designed or modified to be used with equipment specified in 9.A.

Note:
Equipment specified in 9.B.1. includes the following:
a. For laser gyro equipment, the following equipment used to characterise mirrors, having the threshold accuracy shown or better:
1. Scatterometer (10 ppm);
2. Reflectometer (50 ppm);
3. Profilometer (5 Angstroms);
b. For other intertial equipment:
1. Inertial Measurement Unit (IMU) Module Tester;
2. IMU Platform Tester;
3. IMU Stable Element Handling Fixture;
4. IMU Platform Balance Fixture;
5. Gyro Tuning Test Station;
6. Gyro Dynamic Balance Station;
7. Gyro Run-In/Motor Test Station;
8. Gyro Evacuation and Filling Station;
9. Centrifuge Fixture for Gyro Bearings;
10. Accelerometer Axis Align Station;
11. Accelerometer Test Station;
12. Fibre Optic Gyro Coil Winding Machines.

9.B.2. Equipment as follows:
a. Balancing machines having all the following characteristics:
1. Not capable of balancing rotors/assemblies having a mass greater than 3 kg;
2. Capable of balancing rotors/assemblies at speeds greater than 12,500 rpm;
3. Capable of correcting unbalance in two planes or more; and
4. Capable of balancing residual specific unbalance of 0.2 g mm per kg of rotor mass;
b. Indicator heads (sometimes known as balancing instrumentation) designed or modified for use with machines specified in 9.B.2.a.;
c. Motion simulators/rate tables (equipment capable of simulating motion) having all of the following characteristics:
1. Two axes or more;
2. Designed or modified to incorporate sliprings or integrated non-contact devices capable of transferring electrical power, signal information, or both; and

3. Having any of the following characteristics:
a. For any single axis having all of the following:
1. Capable of rates of 400 degrees/s or more, or 30 degrees/s or less; <u>and</u>
2. A rate resolution equal to or less than 6 degrees/s and an accuracy equal to or less than 0.6 degrees/s.
b. Having a worst-case rate stability equal to or better (less) than plus or minus 0.05% averaged over 10 degrees or more; <u>or</u>
c. A position "accuracy" equal to or (less) better than 5 arc second;
d. Positioning tables (equipment capable of precise rotary positioning in any axes) having the following characteristics:
1. Two axes or more; <u>and</u>
2. A positioning "accuracy" equal to or less (better) than 5 arc second;
e. Centrifuges capable of imparting accelerations above 100 g and designed or modified to incorporate sliprings or integrated non-contact devices capable of transferring electrical power, signal information, or both.

<u>Notes:</u>
1. The only balancing machines, indicator heads, motion simulators, rate tables, positioning tables and centrifuges specified in Item 9 are those specified in 9.B.2.
2. 9.B.2.a. does not control balancing machines designed or modified for dental or other medical equipment.
3. 9.B.2.c. and 9.B.2.d. do not control rotary tables designed or modified for machine tools or for medical equipment.
4. Rate tables not controlled by 9.B.2.c. and providing the characteristics of a positioning table are to be evaluated according to 9.B.2.d.
5. Equipment that has the characteristics specified in 9.B.2.d. which also meets the characteristics of 9.B.2.c. will be treated as equipment specified in 9.B.2.c.
6. Item 9.B.2.c. applies whether or not sliprings or integrated non-contact devices are fitted at the time of export.
7. Item 9.B.2.e. applies whether or not sliprings or integrated non-contact devices are fitted at the time of export.

Nature and Purpose: Alignment, calibration, and test equipment is used to build, calibrate, test, and characterize these instruments to meet their requirements. Gyroscopes, accelerometers, and IMUs are precision instruments that must be accurate and reliable over time. Particularly important is test equipment that subjects an instrument to accelerations and orientation changes while measuring the instrument's response over time. This equipment is essential to the manufacture of high quality inertial instruments. Any specially designed test, calibration, alignment, and production equipment is controlled even if it is not specified on the list.

Typical Missile-Related Uses: This equipment is required to produce and calibrate inertial instruments for use in missiles of all types.

Other Uses: Most spacecraft, aircraft, and other vehicles using inertial navigation or guidance units require similar equipment and technologies for development, production, test, and calibration. However, many other non-missile applications can use inertial instruments with higher drift rates, lower vibration and acceleration tolerances, and lower stability requirements. Thus, the test, calibration, alignment, and production equipment for non-missile inertial equipment is often less sophisticated and less precise than that required for accurate missiles.

Appearance (as manufactured): Specially designed alignment, calibration, test, and production equipment for these guidance and navigation items described in 9.A. are usually limited-production items. They are as diverse in size, weight, and appearance as they are in function, and these features change as the technology changes. Although far from a complete list, short descriptions of some examples are provided below.

Because ring laser gyros sense the phase change of minute wavelengths in light, their accuracy is determined by the quality of their mirrors. The mirrors must be a precise shape and reflect almost all the light falling on them and neither absorb nor scatter it. The following three pieces of equipment are designed to characterize mirrors for use in such gyros.

A scatterometer measures the tendency of a mirror to scatter light away from its intended direction to an accuracy of 10 ppm or less. It provides a beam of known intensity and measures the intensity of scattered rays.

A reflectometer measures the ability of a mirror to reflect light to a measurement accuracy of 50 ppm or less. It works by shining a beam of known intensity on the mirror and measuring the intensity of the reflected light.

A profilometer measures the profile of the optical surface of a mirror to an accuracy of 5 Angstroms (5 x 10^{-10} m) or less. Various methods are used to map the minute variations in the optical surface. This mapping helps determine the localized deviations from theoretical perfect geometry, whether it is designed to be flat, concave, or convex.

The accuracy of inertial guidance systems is determined by the quality of their accelerometers and gyroscopes. Most of the following equipment either characterizes or tests these instruments as they operate separately, as an assembly, or as a complete IMU.

An IMU Module Tester operates an IMU module electrically, simulates inputs, and collects response data to confirm proper electrical operation. An IMU Platform Tester operates a complete IMU platform, that is, the stable element or fully operational strapdown IMU. A three-axis rate table, also referred to as a motion simulator, is often used as part of an IMU platform tester. Such tables are controlled under Item 9.B.2.c. An IMU tested by this equipment should correctly sense the earth's gravity and rotation through

all orientation changes without misinterpreting it as lateral or vertical movement and without losing track of its initial alignment with respect to a fixed coordinate reference frame.

An IMU Stable Element Handling Fixture safely handles the IMU stable element, that is, the inner portion of a gimbaled or floated IMU, which contains the inertial instruments. Careful handling facilitates numerous necessary manipulations without degrading the stable element during its assembly, test, and adjustment.

An IMU Platform Balance Fixture determines IMU platform imbalance and thereby facilitates adjustments to establish balance. The center of balance must be established accurately to avoid torques under acceleration and vibration during flight.



Figure 93: A typical rate table used for tuning gyros. (Ideal Aerosmith, Inc)

A Gyro Tuning Test Station energizes the gyro at the desired voltage over a range of speeds to determine the best operating rate of rotation, or rpm. The best rpm is achieved when the effects of gyro error sources are minimized as indicated by data collected. A typical rate table used as part of a gyro tuning test station is shown in Figure 93 and Figure 94.

A Gyro Dynamic Balance Station precisely balances the high-speed rotating members of spinning mass gyroscopes. Balance is critical to gyro performance and longevity. These balancing machines are subject to control under Item 9.B.2.a. if they have the specified performance characteristics.

A Gyro Run-In/Motor Test Station energizes the gyro or gyro motor at the desired voltage and frequency to accumulate run time and thereby break in the gyro bearings and measure motor performance at the design rpm.

A Gyro Evacuation and Filling Test Station purges a gyro internal cavity and fills it with the design pressure of a desired liquid or blend of gases. Most gyros and accelerometers will be filled with an inert dry gas to improve long term performance. In addition, certain gyros have internal cavities that need either a specific liquid of a given density and viscosity or a specific blend of gases to function properly.

A Centrifuge Fixture for Gyro Bearings facilitates testing of gyros in a centrifuge to confirm the ability of the bearings to withstand the acceleration forces expected during flight. Centrifuge fixtures are also used to remove excess lubricant from a gyro's bearing retainer rings.

An Accelerometer Axis Align Station checks accelerometer axis alignment by rotating the accelerometer about its input axis while the input axis is horizontal. This test is often repeated after vibration tests or temperature cycles to determine input axis alignment stabilities. Accelerometer input axis alignment is again checked after installation at the IMU level to determine the slight but important deviations from desired mutual perpendicularity of the input axis.

Accelerometer Test Stations are used to test the accuracy with which an accelerometer can measure gravity over a range of positions and angles. These data are then used to calibrate the instrument. Accelerometers are mounted to a vertical table surface and tumbled to experience gravitational acceleration while upright and alternately upside down. Accelerometer test stations can run tests that include temperature control, using data recording equipment that take data over a long period of time.

Fiber Optic Gyro Coil Winding Machines are used to wind the spool of optical fiber at the heart of Fiber Optic Gyroscopes (FOGs). FOG optical fibers are typically wound using a complex process known as quadrupole winding while enacting strict process controls to insure optimum fiber tension, avoid fiber twisting, achieve positive surface contact and eliminate gaps with subsequent loss of fiber curvature. This exacting process of winding delicate optical fiber onto the spool is a critical step in the manufacture of a high-quality FOG.

Balancing machines are used primarily to balance spinning mass gyroscopes to a high level of precision. Balancing machines are controlled under Item 9.B.2.a.



Figure 94: A two axis rate integrating gyro test station utilizing a motion simulator / rate table. (Contraves, Inc)

Indicator heads are precision round steel tables that can be rotated and locked in a specific direction repeatedly without loss of accuracy. They are also known as tumble testers, indexing heads, positioning tables, and dividing heads. Indicator heads modified for use in balancing machines listed in Item 9.B.2.a. are controlled under Item 9.B.2.b., and high precision, multi-axis indicator heads (i.e., positioning tables) are controlled under Item 9.B.2.d.

Controlled motion simulators and rate tables are precision machines that rotate a mounting table about multiple axes at precisely known speeds and angles. They are normally used in guidance development to test instruments and IMU assemblies as described above. Figure 95shows a two-axis, rate-integrating gyro motion simulator. Rate tables are controlled under Item 9.B.2.c.







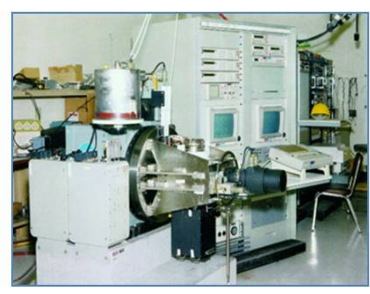


Figure 95: *Left*: a profilometer system used for measuring mirrors. (Digital Instruments) *Middle left*: is another portable IMU tester connected to a miniature IMU. (Litton Guidance and Control Systems) *Middle right*: is a three-axis table for testing IMUs or gyros.

A centrifuge is used as part of an accelerometer test station in order to determine accelerometer non-linearities over a range substantially in excess of the plus and minus one g available in tumble tests. Centrifuges are controlled under Item 9.B.2.e.

Appearance (as packaged): Packaging varies greatly with the size, weight, and sensitivity of the specific equipment. However, because most of these items are precision equipment sensitive to shock or rust, packaging is likely to be robust, with padding and coverings to protect against shock and moisture. Much of the equipment can be disassembled and shipped in separate containers or crates.

9.C. Materials

None.

9.D. Software

9.D.1. "Software" specially designed or modified for the "use" of equipment specified in 9.A. or 9.B.

- Austria
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Norway
- Pakistan
- Russian Federation
- South Africa
- Spain
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: Integrated flight instrument systems use software to interpret and translate information collected from outside the airframe into reconnaissance, target homing or guidance information. Gyro-astro compasses, ring laser gyroscopes and sensitive inertial instruments used in other applications can be installed and used in missile-system navigation systems as sensors used with a flight computer to determine highly accurate acceleration, velocity and position information. Each of these systems requires specialized software that incorporates sensor output and compensates for error signals, such as drift.

Terminal guidance software integrates the output from many sensors to guide the released weapon to its target. Especially rugged accelerometers are used in re-entry vehicles to determine the magnitude of rapid deceleration. The weapon may be enabled or activated when the deceleration value is at a predetermined value.

Software installed on a UAV flight computer is used to launch and fly the UAV to its target and activate the payload (camera, weapon, etc.) once over the target. UAV inertial guidance systems may be augmented by additional systems that make use of ground radio signals, GNSS signals or astro-gyroscope assemblies that identify celestial points of reference.

Other types of software are used to test, calibrate and align guidance system assemblies. Guidance system components are placed on test stations and are subjected to a variety of tests designed to measure such characteristics as drift and scale factors. Seemingly identical instruments will have characteristics that vary from one unit to another. Each device must be characterized. The data collected by these tests are added to the flight program as a form of correction factor for that instrument.

Method of Operation: The integrated flight instrument system forms a series of redundant navigation systems that result in highly accurate navigation. A gyro-astro compass installed in a UAV or rocket system uses navigation software to determine (upon receipt of one or more “star locks”) its velocity, location and heading. Automated navigation systems can use this concept to follow preprogrammed flight paths to its target area. Gyroscopes are used to maintain inertial platform orientation in space while the rocket or UAV system is on the ground and through powered flight. Flight software subroutines contain correction factors such as drift-rate data. The flight computer processes this information and issues correcting signals to torquing motors mounted in the platform gimbals. These motors maintain the platform in a stable orientation throughout flight. Information from accelerometers mounted on the stable platform is sent to the flight computer as acceleration data. Flight software collects this data and, after incorporating additional integrated flight instrument system data, issues steering and control signals to steer the airframe to the target.

Special versions of flight software incorporate the output signals from additional navigation sensors to update or augment inertial guidance data. Gyro-astro compasses send star or satellite position data to the flight computer. Software in the flight computer can use this data to update position information or augment inertially sensed acceleration data. Ring laser gyros provide highly accurate platform misalignment information that can be used to maintain stable platform orientation throughout a number of flight maneuvers and flight accelerations.

Test and calibration stations are used to measure guidance system defects, such as gyro drift, and provide characterization data used in the flight program to compensate for these deficiencies. Alignment stations confirm the quality and appropriateness of the installation and calibration of inertial instruments on the stable platform. These procedures take the longest development time and add the greatest cost to each instrument. Identical instruments manufactured on common equipment require detailed testing and calibration to precisely determine the individual characteristics.

Typical Missile-Related Uses: The type of software controlled under Item 9.D.1. is used to provide highly accurate UAV and rocket system navigation. Automated machining equipment is required to produce the precision components that make up the inertial guidance instruments. Once these components are assembled, they are tested and their performance is evaluated on computer-operated test stations. The

results of this testing produce data that is used to both characterize the instrument, such as drift rate and scale factor, and define guidance system constants in the flight software.

Other Uses: Elements of integrated flight instrument systems (radar, laser systems and direction-finding equipment) are all used in civil and military aircraft to augment inertial navigation systems. Lesser-quality inertial navigation components may be used in measurement while drilling applications. Software used to test, calibrate and align these instruments is found in civil and military aircraft test and repair facilities.

Appearance (as manufactured): Software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

9.D.2. Integration "software" for the equipment specified in 9.A.1.

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Norway
- Pakistan
- Russian Federation
- South Africa
- Spain
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: Rocket or UAV system integration software for the equipment specified in 9.A.1. is used to couple the output of a gyrostabilizer, an autopilot or other integrated flight instruments to the flight computer. The flight computer then incorporates information from these auxiliary navigation devices with data provided by the instruments mounted within the inertial navigation system. The result is accurate guidance and steering commands using less expensive navigation instruments.

Method of Operation: Rocket or UAV system navigation software stored in the flight computer accepts information from the integrated flight instrument system. This position information is evaluated against the planned trajectory, and the flight computer issues correction or steering commands to the flight control system.

Typical Missile-Related Uses: This software is used to support UAV and rocket system navigation.

Other Uses: This software may also be used to support civil and military aircraft guidance systems.

Appearance (as manufactured): Typically this software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

9.D.3. Integration "software" specially designed for the equipment specified in 9.A.6.

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Norway
- Pakistan
- Russian Federation
- South Africa
- Spain
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: Integration software specially designed for the equipment or systems specified in 9.A.6. is used to integrate gyroscopes, accelerometers and inertial or stable platform assemblies that are used in non-guidance applications (such as satellite tracking antennae, video cameras, etc.) into UAV or rocket system guidance and control applications.

Method of Operation: Higher-quality inertial guidance instruments such as gyroscopes, accelerometers and sufficiently ruggedized stable platforms used to steady camera platforms, guide drilling mechanisms, etc. may be used as core rocket and UAV system guidance system components with the application of appropriate integration software. This software is similar to the inertial measurement unit software designed for specific flight vehicle guidance applications. It is written and tested using the same test and calibration equipment as that used for the more specialized guidance system hardware.

Typical Missile-Related Uses: This software is used solely to support UAV and rocket system navigation.

Other Uses: Elements of integrated flight instrument systems (radar, laser systems and direction finding equipment) are all used in civil and military aircraft to augment inertial navigation systems. Software used to test, calibrate and align these instruments is found in civil and military aircraft test and repair facilities.

Appearance (as manufactured): Typically, this software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

9.D.4. Integration "software", designed or modified for the 'integrated navigation systems' specified in 9.A.7.

Note:
A common form of integration "software" employs Kalman filtering.

Nature and Purpose: Integration software, designed or modified for the integrated navigation systems specified in 9.A.7. integrates the outputs of inertial measurement instruments and other external sensors into a system that provides information used by the flight computer to continuously compute altitude, position and velocity information. Kalman filtering is a software procedure that estimates a vehicle's position and velocity in time based on the known performance of the flight vehicle and then periodically updates that estimate using filtered information provided by other guidance system components. The filter used in rocket or UAV system flight navigation evaluates the position information signals to eliminate random or erroneous measurements (noise) from other integrated navigation system instruments.

Method of Operation: Rocket or UAV system flight software can be written or modified to incorporate this integrating software. It is initially tested using the same test and calibration equipment as that used for the more specialized guidance system hardware and proven using a series of flight tests.

Typical Missile-Related Uses: This software is used to support highly accurate UAV and rocket system navigation.

Other Uses: This software may also be used to support civil and military aircraft guidance systems.

Appearance (as manufactured): Typically, this software takes the form of a computer program stored on printed, magnetic or other media. Any common media including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

Note:
Equipment or "software" specified in 9.A. or 9.D. may be exported as part of a manned aircraft, satellite, land vehicle, marine/submarine vessel or geophysical survey equipment or in quantities appropriate for replacement parts of such applications.

9.E. Technology

9.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or "software" specified in 9.A., 9.B. or 9.D.

Note:
Equipment or "software" specified in 9.A. or 9.D. may be exported as part of a manned aircraft, satellite, land vehicle, marine/submarine vessel or geophysical survey equipment or in quantities appropriate for replacement parts for such applications.

- Argentina
- Australia
- Brazil
- China
- Denmark
- France
- Germany
- India
- Israel
- Italy
- Japan
- Russian Federation
- South Korea
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: Rocket or UAV system guidance system technology resolves very complicated dynamic control problems. Missile and guidance engineers must know all the physical aspects of the devices used to produce accurate navigation. This knowledge is usually gained through a series of computer modeling, bench testing and flight testing exercises. Integrating diverse navigation tools such as an autopilot, gyro-stabilized platforms and other active components such as radar, laser or GPS receiver is a complex task. Developing test and production equipment to support this activity is equally challenging. The designer must know as completely as possible the precise characteristics of the devices that will be tested and interconnected on the test bench in order to develop the required simulation software. Production managers may design and construct guidance system production and integration equipment based on the final designs determined in the laboratories. Much of the technology needed to complete these tasks comes only with experience.

Method of Operation: Early in a development program, design integration technology is often manifested in a computer program that models the airframe and the propulsion, guidance and control systems of the vehicle. The software simulates guidance system behavior in all expected flight regimes and predicts

theoretical performance. The designer can change the subsystem parameters, rerun the simulation and choose those parameters that give the best performance. Later in the development program “hardware-in-the-loop” simulations may be used where actual guidance components and subsystems are connected together on a test bench. The computer simulates the flight environment and any hardware missing from the simulation.

Typical Missile-Related Uses: This technology is used to provide and improve guidance system performance and accuracy for rocket and UAV systems. Equally important are the requirements to design, develop, produce and use ground test and checkout equipment and software.

Other Uses: This technology may also be used to manufacture components used to accurately point parabolic antennae, stabilize video cameras for long-range photography (including ballistic missile test range instrumentation), and other civilian and military purposes.

Appearance (as manufactured): N/A.

Appearance (as packaged): N/A.

Category II - Item 10

Flight Control

Item 10 – Flight Control

10.A. Equipment, Assemblies and Components

10.A.1. Pneumatic, hydraulic, mechanical, electro-optical, or electromechanical flight control systems (including fly-by-wire and fly-by-light systems) designed or modified for the systems in 1.A.

- Australia
- Austria
- Belgium
- Brazil
- Canada
- China
- Czech Republic
- Egypt
- France
- Germany
- Greece
- Hungary
- India
- Israel
- Italy
- Japan
- Norway
- Portugal
- Romania
- Russian Federation
- South Africa
- Republic of Korea
- Sweden
- Switzerland
- Turkey
- United Kingdom
- United States

Global production



Nature and Purpose: The flight control system provides and controls the steering mechanisms needed for a rocket or UAV system to achieve stable flight and execute subsequent maneuvers without losing stability. It normally receives steering commands from the guidance set, mission computer or integrated flight instrument system.

The flight control system includes the actuators to move control surfaces, aim nozzles, control flows and activate thrusters. It also includes sensors to detect changes in attitude, rate of change of attitude, speed, altitude, throttle setting, air temperature and air pressure. These sensor outputs are often shared by other mechanisms in the rocket or UAV. The flight control system is distributed throughout the rocket or UAV and sometimes overlaps with portions of other systems.

Information transmitted from the sensors to the flight control computer and to the actuators is either analog or digital and may be routed by electrical wires (fly-by-wire). State-of-the-art systems may use optical fibers (fly-by-light) to provide digital communication between the flight control components. Optical connections are lighter in weight and greatly reduce susceptibility to the effects of electromagnetic pulse, electromagnetic interference, and lightning.

Method of Operation: When UAV systems, including cruise missiles, need to maneuver (turn, climb, etc.), the integrated flight instrument system commands a change in heading or altitude. The flight control system adjusts the actuators for control surfaces to introduce pitch, roll, and/or yaw; holds those settings until the orientation has changed; and then resets the actuators to maintain the new profile. Flight control systems often work in conjunction with a gyrostabilizer or automatic pilot (autopilot), which determines the control surface motions necessary to achieve the desired maneuvers. Autopilots also continuously compensate for environmental disturbances. Rocket systems may also use flight control systems that

operate similarly, but rockets use thrust vector control and sometimes small steering jets to change direction. Some rocket systems also use aerodynamic fins while in the atmosphere.

Typical Missile-Related Uses: Flight control systems are required to achieve stable flight and execute maneuvers without losing stability. These systems are usually tailored to the flight characteristics and mission profile of the rocket or UAV system and thus tend to be system-specific. Most rockets and UAVs use these systems.

Other Uses: Components used in missile flight control systems may also be used in military and civilian aircraft.

Appearance (as manufactured): The flight control system is not a single integral unit; it is distributed throughout the missile. The flight control system parts most likely to be encountered include the actuators, electronic assemblies, specialized cables and some sensors.

Appearance (as packaged): Aerodynamic control surfaces and actuators are fairly robust pieces of equipment. Typical packaging includes wooden crates and cardboard or wooden boxes. They are securely attached to the shipping container to avoid movement and probably packed in foam shaped like the part. The sensors used in flight control systems are often more delicate and are normally individually wrapped and secured in a shock-resistant box or crate. They are often wrapped in a moisture-proof bag.

10.A.2. Attitude control equipment designed or modified for the systems specified in 1.A.

- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Russian Federation
- United Kingdom
- United States

Global production



Nature and Purpose: Attitude control is different from guidance. Guidance centers on the assurance that a vehicle reaches a predetermined position at a given time. Attitude control makes sure that the airframe has a certain orientation in space at given times. There are three fundamental methods of controlling the attitude of a flight vehicle: use of aerodynamic forces (wings), deflecting the thrust of the main rocket engine and the use of auxiliary thrust-producing devices.

Method of Operation: The actuators used to move a UAV's aerodynamic control surfaces can either be rotary or linear. A rotary actuator can be powered by an electric motor and responds proportionally to an input command. The actuator is part of a closed-loop control system, which includes an amplifier and a method for sensing the position of the actuator. The mechanical output of the actuator is either a hub that can accept a control surface shaft or a shaft onto which a surface can be mounted. An actuator for thrust vector control (TVC) used on rockets, including space launch vehicles, is shown in Figure 96. A linear actuator used to control the pitch of rotor blades on UAVs is shown in Figure 97. Sometimes an actuator must not only be

capable of rotating the control surface into a significant aerodynamic force but also supporting the entire mass of the surface during high-acceleration launches and maneuvers. Linear actuators are connected to control surfaces through mechanical linkages that convert the linear actuator motion to an angular control surface motion. These actuators are powered by an electric motor, pressurized gas or hydraulic fluid.



Figure 97: An electromechanical thrust vector control subsystem, with linear actuator and associated electronics box, used on rockets, including space launch vehicles. (Moog, Inc)



Figure 96: A linear actuator used to position the pitch of rotor blades on a tilt rotor unmanned aerial vehicle and designed to operate under extreme environmental and endurance conditions. (Moog, Inc)

Typical Missile-Related Uses: UAV system fins and rudders are used to correct inaccuracies in the flight path that are detected by the guidance system or to initiate steering commands to a new course heading or altitude. Rocket system thrust vector control devices are used for the same purposes.

Other Uses: Components used in UAV and rocket system flight control systems may also be used in military and civilian aircraft.

Appearance (as manufactured): Flight control system components are distributed throughout the missile. Sensors, amplifiers and other components are housed in sealed boxes. Actuators are collocated or integrally manufactured with a flight control surface. The actuators used to move a UAV’s aerodynamic control surfaces, including for cruise missiles, can either be rotary or linear.

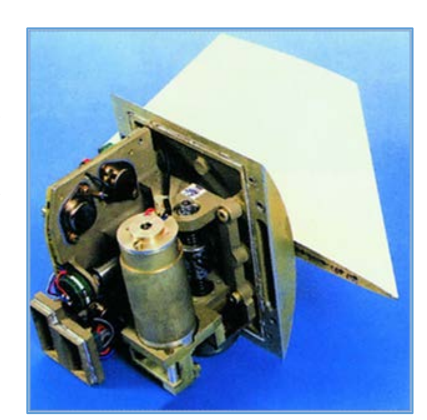


Figure 98: An electromechanical flight control actuator for a tail fin of a small missile. (Daimler Benz Aerospace)

Appearance (as packaged): Aerodynamic control surfaces and actuators are fairly robust pieces of equipment. Typical packaging includes wooden crates and cardboard or wooden boxes. They are securely attached to the shipping container to avoid movement and probably packed in foam shaped like the part. The sensors used in flight control systems are often more delicate and are normally individually wrapped and secured in a shock-resistant box or crate. They are often wrapped in a moisture-proof bag.

10.A.3. Flight control servo valves designed or modified for the systems in 10.A.1. or 10.A.2., and designed or modified to operate in a vibration environment greater than 10 g rms between 20 Hz and 2 kHz.

Note:
Systems, equipment or valves specified in 10.A. may be exported as part of a manned aircraft or satellite or in quantities appropriate for replacement parts for manned aircraft.

- China
- France
- Israel
- Japan
- Russian Federation
- United Kingdom
- United States

Global production



Nature and Purpose: A servo valve is an electrically-operated valve that uses feedback to precisely control the position of an internal device (either flapper nozzle or jet pipe) to control the fluid flow. The term electrohydraulic servo valve is often used because servo valves are controlled through an electrical signal and are usually used in hydraulic systems. Servo valves operate with very high accuracy, very high repeatability, very low hysteresis, and very high frequency response. Servo valve systems feature high response characteristics, high reliability, accurate position control, velocity control and force control.

Servo valves are used when accurate position control is required, such as control of a primary flight control surface. Position control is achieved through a closed loop control system, consisting of command sensor, feedback sensor, digital or analog controller, and the servo valve. Servo valves can be used to control hydraulic actuators or hydraulic motors. A servo valve and actuator combination are referred to as a servo-actuator. The main advantage of a servo valve is that a low power electrical signal can be used to accurately position an actuator or motor.

Method of Operation: The primary components in a servo valve are a torque motor, flapper nozzle or jet pipe, and one or more spools (servo). Servos in aerospace servo valves are typically zero lapped, which means the width of the lap and the width of the flow port are equal. Thus, there is only one position for zero flow. This configuration generally results in the tightest control and is commonly selected for high precision servo valves.

The servo valve has a hydraulic pressure inlet and an electrical input for the torque motor. The input current controls the flapper position. The flapper position controls the pressure in the chambers of the actuator. So, a current (+ or -) will position the flapper, leading to a pressure differential on the servo, which causes the servo to move in one direction or the other. Movement of the servo ports hydraulic pressure to one side of the actuator or the other, while porting the opposite side of the actuator to return.

Most servo valves incorporate a feedback spring between the pilot spool and the flapper. If the flapper moves to the left, the pressure differential on the pilot spool moves the spool to the right. The feedback

wire will then pull the flapper back towards the neutral position. Hence the feedback wire provides a stabilizing force to the flapper and helps improve stability and response of the flapper system. Servo position is determined by a force balance on the spool, which includes the pressure differential created from the flapper nozzle, friction forces, spring forces and flow forces acting on the spool.

Typical Missile-Related Uses: Thrust vector control (TVC) is used when the aerodynamic surfaces are inadequate to control the missile or when a greater agility may be required of the missile. The TVC subsystem is used to gimbal the entire rocket engine (typical for liquid engines) or gimbal the rocket nozzle (typical for solid rocket motors) or move jet vanes in the nozzle section of the thrust chamber to provide precise steering for the missile. The gimbal or jet vane movement is accomplished by actuators. The motions of the hydraulic actuators are controlled by servo valves, which in turn are controlled by commands from the vehicle's guidance system.

Other Uses: Servo valves are encountered in a wide range of modern industrial applications because of their ability to handle large inertia and torque loads and, at the same time, achieve fast responses and a high degree of both accuracy and performance. Typical applications include active suspension systems, control of industrial robots, and processing of plastic. They are also ubiquitous in commercial aircraft, satellites, launch vehicles, flight simulators, turbine control, and numerous military applications.

Appearance (as manufactured): Servo valves used in flight control systems may be constructed from stainless steel and have mounting swivels at either end. Hydraulic and electrical connections will be found on the side of the device. Position indicators provide feedback signals to the flight computer and may be available through a separate electrical connector.

Appearance (as packaged): Flight control servo valves are fairly robust pieces of equipment but they have sensitive position indicator mechanisms attached or built into the case. Typical packaging includes cardboard or wooden boxes. They are securely attached to the shipping container to avoid movement and probably packed in foam shaped like the part. They are often wrapped in a moisture-proof bag.

10.B. Test and Production Equipment

10.B.1. Test, calibration, and alignment equipment specially designed for equipment specified in 10.A.

Nature and Purpose: Flight control system test, calibration and alignment equipment includes the specialized jigs and fixtures necessary to mechanically support and to provide power and electric test signals to sensor electronics and actuator subsystem components. These pieces of test equipment may also be used to support actuator and other subcomponent-level calibration, alignment, functional, and operational testing. They take the form of test stands and benches using either water or some other fluid as a stimulant or using the hydraulic fluids or propellants that will be employed during operational use.

Method of Operation: Test section computers provide simulated steering and correction signals to units of the flight control system under test conditions and record the resulting actuator or control surface motion. Each subsystem can be evaluated for accuracy of motion as well as rate of change and maximum frequency response. Test stations often contain equipment that is used to confirm the aerodynamic control surface alignment to null and commanded positions.

Typical Missile-Related Uses: Flight control systems are tuned circuits that use feedback information from actuators or other sensors. Test equipment detailed in this section not only test, calibrate, and align control surfaces relative to input signals, but also capture the output data used to calibrate and characterize an actuator's performance. These data are used in the flight program to define individual actuator response and performance features.

Other Uses: This test equipment may also be used to test, align and calibrate flight control equipment used in military and civilian aircraft.

Appearance (as manufactured): Flight control test equipment looks like standard laboratory apparatus found in larger universities or aerospace industries, such as wind tunnels, electronic test benches, laser calibration devices, hydraulic or hydrodynamic test benches, etc. The equipment will consist of electronic test equipment, possibly computer controlled, electric and possibly hydraulic power supplies and rigid mechanical equipment to mount flight control actuators and control surfaces. Calibration points and alignment fixtures may be incorporated into these mountings.

Appearance (as packaged): New equipment or replacement spare parts are shipped separately in crates or protected on pallets for onsite assembly. They will be securely fastened to the crate to restrain motion and prevent damage. Smaller jigs may be individually crated or palletized for shipment. Test equipment is usually fragile and is so marked. It will include computer equipment, test stations, and corresponding support and interface components. There may be hydraulic pressurization systems and precision alignment fixtures included with the assemblies. Larger items may be palletized or crated in large wooden or metal crates, while smaller items will be in cardboard or wooden boxes.

10.C. Materials

None.

10.D. Software

10.D.1. "Software" specially designed or modified for the "use" of equipment specified in 10.A. or 10.B.

Note:
"Software" specified in 10.D.1. may be exported as part of a manned aircraft or satellite or in quantities appropriate for replacement parts for manned aircraft.

- Australia
- Austria
- Belgium
- Brazil
- Bulgaria
- Canada
- China
- Czech Republic
- Egypt
- France
- Germany
- Greece
- Hungary
- India
- Israel
- Italy
- Japan
- Norway
- Portugal
- Romania
- Russian Federation
- South Africa
- Republic of Korea
- Sweden
- Switzerland
- Taiwan
- Turkey
- United Kingdom
- United States

Global production



Nature and Purpose: Flight software used in UAV and rocket systems provides control and steering commands sent to the flight control system actuators. These actuators then change the position of UAV control surfaces or alter the rocket thrust vector or aerodynamic surfaces to modify the flight trajectory. Other software is used to test, calibrate, align, and maintain the flight control system sensors and instruments and the actuator hardware.

Method of Operation: Flight control system software tells the flight controller (the "brains" of the system) how to interpret and translate the information supplied from the guidance sensors into steering commands to individual flight control actuators. These commands continuously correct the vehicle's flight trajectory as minor errors are detected in the angular orientation (rocket or UAV pointing direction) and in the flight path. They may also be used to steer the vehicle to a new flight heading following the course and trajectory information stored in the main flight computer. Various types of ground support software are used in laboratory and maintenance facilities to test the sensor and actuator hardware or to calibrate and maintain the system after one or more parts have been replaced. Computers connected to test-bench equipment may provide appropriate simulation signals to a flight control sensor device and measure its output. The sensor output is also provided to the control actuator and the test equipment measures its output. Lasers or other high-quality measuring tools are used to determine the accuracy of alignment and motion for rocket nozzle steering, or similarly for aerodynamic control surfaces. Based on design specifications, the repair technician can then make adjustments to bring the equipment to design tolerances.

Typical Missile-Related Uses: Flight control system software is loaded into the UAV or rocket system flight computer memory and is usually a functional part of the flight software. It is used during flight to monitor the position and trajectory supplied by the guidance system. The flight computer issues steering commands, after evaluating this data with preprogrammed information, to individual flight control actuators to correct any detected position errors.

Other Uses: Software used in UAV and rocket flight control systems may also be used in military and civilian aircraft. The ground support software may also be used in these industries to test and maintain aircraft and rocket control systems. Software for self-driving cars has underlying similarities to software for steering rockets and UAVs, although the detailed implementation differs significantly.

Appearance (as manufactured): This software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media – including magnetic tape, floppy disks, removable hard disks, USB flash drives, compact discs and documents – can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, USB flash drives, compact discs and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network such as the internet.

10.E. Technology

10.E.1. Design "technology" for integration of air vehicle fuselage, propulsion system and lifting control surfaces, designed or modified for the systems specified in 1.A. or 19.A.2., to optimise aerodynamic performance throughout the flight regime of an unmanned aerial vehicle.

Nature and Purpose: Stable and controlled atmospheric flight is a very complicated dynamic control problem. Solving it requires in-depth knowledge of all subsystems and their interactions over all flight regimes. This knowledge is normally generated by wind tunnel testing, computer modeling to simulate vehicle performance, and a detailed flight test program. Design integration technology enables designers of UAV systems (including cruise missiles) to size, configure, and optimize all the subsystems; to take into account their often-complicated interactions; and thereby to minimize errors. Thus, this technology decreases the time to design, test and produce a UAV and may also support efforts to improve performance.

Method of Operation: Design integration technology typically includes a specially designed computer program used early in a UAV development program, and later refined, to model the aerodynamic characteristics of the airframe, along with the propulsion, and guidance and control systems of the vehicle. The designer can change the flight control system parameters, rerun the simulation, and choose parameters that give the best performance. Later in the development program, “hardware-in-the-loop” simulations may be used that integrate flight control systems together on a test bench, while these

systems are connected to a computer simulating the flight environment. Other test equipment, such as wind tunnels, may be used to replicate flight conditions and aerodynamic responses as part of the simulations.

Typical Missile-Related Uses: Design integration technology is used to design and integrate flight control systems found in UAV systems, including cruise missiles.

Other Uses: Some “technology” used to design, manufacture and test UAV systems may have functionality in the military or commercial aircraft industry. One example is autopilots for crewed aircraft. There are also some overlaps in the know-how needed to develop self-driving cars and non-military UAVs

Appearance (as manufactured): Typically UAV design integration technology takes the form of engineering expertise among people, and this expertise is likely to be reflected in computer programs stored on printed, magnetic, optical or other media. Any common media – including magnetic tape, floppy disks, removable hard disks, USB flash drives, compact disks and documents – can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, USB flash drives, compact disks and documents containing design integration technology are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer or the internet. This technology, including the documentation, can be transmitted over a computer network. Other design integration technology consists of training and hands-on experience at foreign technology centers, for instance at instrumented wind tunnels or hardware-in-the-loop facilities.

10.E.2. Design "technology" for integration of the flight control, guidance, and propulsion data into a flight management system, designed or modified for the systems specified in 1.A. or 19.A.1., for optimisation of rocket system trajectory.

Nature and Purpose: The technology needed to control rocket system flight is complicated and involves a great number of physical variables that must be understood, measured, and adjusted. Not only must designers possess in-depth knowledge of the missile flight control subsystems and their interactions, they must also determine techniques to solve control problems that involve high velocities over a wide range of altitudes. Some of this knowledge may be manifested in computer modeling that is based on subsystem specifications, wind tunnel testing, and a detailed flight test program. As missiles become more advanced, missile development programs involve increasing costs and extended time schedules. As a result, many countries attempt to acquire the needed technology from foreign sources to reduce the time and cost of missile development programs.

Method of Operation: Technical assistance is available in many forms. Technical assistance may consist of instruction provided by a person or organizations experienced with developing flight control systems for rocket systems who acts as a trainer in a classroom on or near the development or production site. A

country may receive technical assistance from one or more foreign entities that possess the design and development facilities needed to provide hands-on experience to grow the desired technology. Technical assistance may also come in the form of assistance in procuring machines, equipment and materials. It is possible for controlled technology transfers to occur as part of bid-and-proposal activity, after a quotation is requested but before any contract is signed or work performed.

Typical Missile-Related Uses: With limited exception, technical assistance required to develop and build rocket flight control systems are used only for those purposes. Sounding rockets used in weather research, with minor adjustments, can be converted to ballistic missiles. The technology used in ballistic missiles, SLVs, and in sounding rockets is very much the same, although sounding rockets do not require accurate trajectory control to reach a precise target location.

Other Uses: This technology has limited to nonexistent application apart from rocket engineering. There are general similarities, and some similar details, to the know-how needed to develop aircraft autopilots, self-driving cars, and commercial UAVs although the high speeds and the wide range of altitudes puts flight control technology for ballistic missiles in a class by itself.

Appearance (as manufactured): Typically, rocket design integration technology takes the form of engineering expertise among people, and this expertise is likely to be reflected in a computer program stored on printed, magnetic, optical or other media. Any common media – including magnetic tape, floppy disks, removable hard disks, USB flash drives, compact disks and documents – can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, USB flash drives, compact disks and documents containing design integration technology are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This technology, including the documentation, can be transmitted over a computer network. Other design integration technology consists of training and hands-on experience at foreign technology centers, for instance at instrumented high-speed wind tunnels or hardware-in-the-loop facilities.

10.E.3. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or "software" specified in 10.A., 10.B. or 10.D.

Nature and Purpose: Technology needed to develop and produce rocket and UAV flight control systems consists of a wide range of engineering and scientific know-how. There needs to be detailed knowledge and working expertise for flight control actuators (as used in Item 10.A.1), the functionality of other attitude control equipment such as jet vanes (covered by Item 10.A.2), and for specialized servo valves (Item 10.A.3) if hydraulic control is used. Similarly, there needs to be detailed knowledge and expertise for producing and testing flight control components and subsystems, including an understanding of test, calibration and alignment equipment (Item 10.B.1). Ultimately, all this technology is derived from experimentation supported by calculations and the laws of physics.

In many cases, translating the above know-how into computer software can reduce the time and expense needed to design and develop rocket or UAV flight controls. Such software may include mathematical representations of flight control systems, propulsion, guidance, and related subsystems. Technology for test, calibration and alignment equipment can similarly be manifested partly as specialized computer software. Much of the know-how needed to implement flight control can be acquired from countries that already have this technology, reducing the time and expense of fresh learning by testing alone.

Method of Operation: General technology for flight control includes many subjects. Implementation usually requires interdisciplinary engineering teams of people working together in a highly organized fashion. It is often productive for a computer program used early in a development program that models the airframe and the propulsion, guidance and control systems of the vehicle. The software simulates vehicle behavior in all expected flight regimes and predicts theoretical performance. The designer can change the subsystem parameters, rerun the simulation, and choose those parameters that give the best performance. Later in the development program, "hardware-in-the-loop" simulations may be used where actual subsystems are connected together on a test bench, and the computer simulates the flight environment and any hardware missing from the simulation. Some test equipment, such as wind tunnels, may be used to replicate actual flight conditions as part of the simulations. This technique finds real-world effects of hardware interactions, which may be difficult to detect or hard to simulate. For example, the U.S. space shuttle was never flight-tested in its final configuration. Although numerous components and subsystems were extensively tested, the shuttle flew with a crew the first time it was launched—an event extremely unlikely without this technology.

Typical Missile-Related Uses: General technology for development and production of missile flight controls is essential to all missiles, in order to follow the desired trajectory and reach the intended target.

Other Uses: Commercial and military aircraft require flight control, the general technology for which includes many overlapping subject areas of technical expertise. Similarly, self-driving cars need electromechanical or hydraulic control actuators for steering. While the detailed implementation of missile flight control may be quite different, the transfer of general technology for these other kinds of vehicles may still be applicable to missile programs.

Appearance (as manufactured): To the extent that the technology resides in software, flight control technology can be stored on printed, magnetic, optical or other media. Any common media – including magnetic tape, floppy disks, removable hard disks, USB flash drives, compact disks and documents – can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, USB flash drives, compact disks and documents containing flight control technology are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This technology, including the documentation, can be transmitted over a computer network or internet.

Category II - Item 11

Avionics

Category II – Item 11: Avionics

11.A. Equipment, Assemblies and Components

Notes:
1. Equipment specified in 11.A. includes the following:
a. Terrain contour mapping equipment;
b. Scene mapping and correlation (both digital and analogue) equipment;
c. Doppler navigation radar equipment;
d. Passive interferometer equipment;
e. Imaging sensor equipment (both active and passive);
2. Equipment specified in 11.A. may be exported as part of a manned aircraft or satellite or in quantities appropriate for replacement parts for manned aircraft.

11.A.1. Radar and laser radar systems, including altimeters, designed or modified for use in the systems specified in 1.A.

Technical Note:
Laser radar systems embody specialised transmission, scanning, receiving and signal processing techniques for utilisation of lasers for echo ranging, direction finding and discrimination of targets by location, radial speed and body reflection characteristics.

Nature and Purpose: Radars and laser radars are sophisticated active sensor systems that can be used for reconnaissance, target homing, or guidance in unmanned aerial vehicles (UAVs), especially cruise missiles. These systems include Laser Detection and Ranging (LADAR) and Light Detection and Ranging (LIDAR) technologies. These terms are often used interchangeably and generically can be used to refer to devices that use laser energy to establish a range or to image an object. Radar scene-matching correlators have been used in UAVs, including cruise missiles, and ballistic missiles. Radar and laser altimeters are somewhat less sophisticated devices used for navigation and terrain avoidance in cruise missiles and weapon fuzing in cruise and ballistic missiles. In recent years, significant technological improvements have occurred in transmitters, receivers, antennas, and electronic processing.

Method of Operation: Radar, LADAR, and LIDAR systems operate similarly. They emit a pulse of electromagnetic energy and detect the energy reflected to them from the terrain or target below. Distance is computed as a product of half the elapsed time between signal transmission and reception, and the speed of light. The direction of the target or terrain is given by the angle between the two pulses. The image of the terrain or target thereby created can be compared with stored images, and missile course can be altered as needed.

- Austria
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Norway
- Russian Federation
- South Africa
- Republic of Korea
- Sweden
- Taiwan
- United Kingdom
- United States





Radar and laser altimeters operate similarly, but measure only the distance from the missile to the ground. Such altimeters make precise measurements of distance above ground to help low flying missiles avoid terrain and, when compared with elevation maps, can be used as navigation aids. Radar altimeters may also be used in altitude fuzing of ballistic missiles.

Doppler navigation systems operate like radar altimeters, but compare the frequencies, not the transit time, of the transmitted beams and the returned energy. The change in frequency (a Doppler shift) is a result of missile movement relative to the ground and can be directly converted to missile velocity. Multiple antennas can measure missile velocity in any direction if they receive enough returned energy. This velocity information can be used to correct for accumulated guidance errors.

Typical Missile-Related Uses: These systems are used in cruise missiles as sensors for target discrimination, homing, and warhead fuzing. They are also used as navigation aids for keeping the missile on a prescribed flight path and at certain flight altitudes. Such sensors can also be used for terminal guidance or fuzing of ballistic missiles.

Other Uses: Radar and Doppler navigation systems are used on military and commercial aircraft and ships for navigation, weather detection, and collision avoidance. Radar altimeters are commonly used for numerous purposes such as determining height above the terrain on many types of aircraft. LIDARs have been used for atmospheric measurements, oceanographic studies, and smokestack emissions studies.

Appearance (as manufactured): Radar systems for rockets and UAVs (seekers or sensors) are normally designed as a single assembly consisting of an antenna subassembly located at one end of the system and the supporting power, control, and processing subassemblies located in one or more (separate but connected) housings. The antenna subassembly is normally a circular or oblong radiating and receiving, beam-forming element linked to both a power amplifier and waveguides, normally rectangular tubing that couples the signal from the amplifier to the radiating element. Antennas are either flat or parabolic and must be sized to fit within the missile diameter. The antennas are fixed in electronically scanning systems or gimbaled in mechanical scanning systems. The antenna-mounting features and support structure are strong enough to maintain stability and accuracy in the presence of substantial accelerations caused by launch, turbulence, and maneuvering.

The shape and weight of the support structure and ancillary equipment housings vary greatly from system to system, but may have some features peculiar to missile applications. For example, to help reduce missile cross-sectional area and improve cooling, the equipment boxes may have one or more cylindrical

or conical surfaces and may have mounting features to ensure good contact with the missile skin or provide for coolant flow rather than external fins for air-cooling.

Radar altimeters are generally much smaller than radar seekers or other sensors with fixed, surface-mounted transmitter and receiver antennas. These antennas, which must point toward the ground, are usually flat, rectangular, or circular plates with a mounting surface conforming to the exterior of the missile. The power- and signal-processing requirements are significantly less than those for radar seeker systems. The transmitter and receiver are normally enclosed within one box connected to the antenna by a coaxial cable. This subassembly usually has a volume of less than 0.05 m^3 and does not require external cooling. A typical Doppler system consisting of a receiver/transmitter/antenna assembly typically occupies 0.007 m^3, weighs less than 5 kg, and requires about 12 watts of power.

LADAR and LIDAR systems differ from radar systems in that they use the much shorter visible-light and IR wavelengths respectively. They are easily distinguished by the external appearance of an optical lens or window. Systems operating at longer IR wavelengths have an optical port that may appear to be metallic. Like radar antennas, the optical unit of the system is fixed or movable, and it may be mounted separately. Construction is heavy, with rugged mounts. In general, all of these systems have mounting surfaces that are unpainted but coated with a conductive anti-corrosion film. The electrical grounding of all avionics chassis is vital to survival in hostile electromagnetic environments.

Appearance (as packaged): Although these systems are built to survive normal missile handling and storage, and severe flight environments, they must be carefully packaged to ensure that unusual stresses are not imposed by the shipping container and its environments. Because the antenna structure and drive systems are especially sensitive, they are well protected. The systems are sealed in an air-tight enclosure and shipped in cushioned containers. A wide range of outer containers may be used including metal drums, wooden boxes, and composite or metal cases.

11.A.2. Passive sensors for determining bearings to specific electromagnetic sources (direction finding equipment) or terrain characteristics, designed or modified for use in the systems specified in 1.A.

•Australia	•China
•France	•Germany
•India	•Israel
•Italy	•Japan
•Norway	•Russian Federation
•South Africa	•Republic of Korea
•Sweden	•Taiwan
•United Kingdom	•United States

Global production



Nature and Purpose: Direction-finding systems provide a vehicle with bearing information (angular orientation) to known sources of electromagnetic radiation emanating from ground-based transmitters. Terrain and target characteristics may be determined by imaging systems, typically a visible or infrared (IR) camera. These systems are passive because they receive but do not transmit energy; thus, missiles using them are much less likely to be detected. Both systems are used for UAV guidance and as payload sensors, and in some cases have been used for terminal guidance of ballistic missiles.

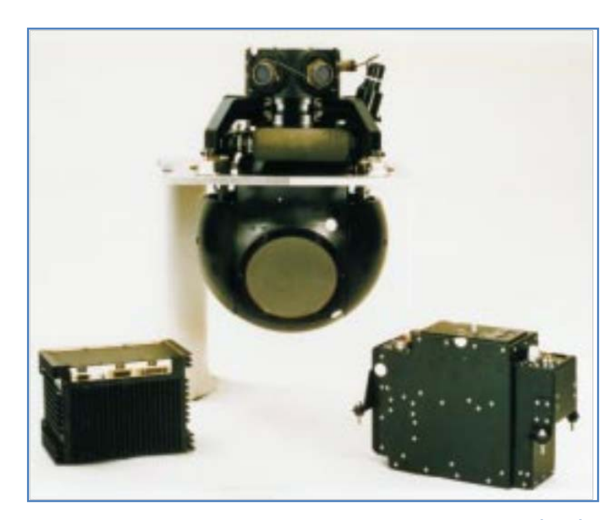


Figure 99: An infrared imaging sensor for a UAV (*top*) and its associated electronics. (LFK-GmbH)

Method of Operation: Direction-finding equipment uses passive sensors to receive electromagnetic radiation from ground transmitters at various known points. For example, comparing the relative transit times of the signals from two or more sites allows the computer on the missile to determine its location and heading. This information is used by the integrated flight instrument system to follow the preprogrammed flight plan. An anti-radiation homing seeker guides the missile to the target by processing the received radar energy from a single emitter.

Imaging sensors may use terrain characteristics to navigate. The optical assembly consists of one or more lenses of fixed or variable focal length, an image intensifier, and a photosensitive array for converting the scene into a digital map. This assembly operates in the visible or IR wavelengths. Visible light systems using a high-intensity flash illuminator at night thus become semi-active sensors. The sensors collect images of ground scenes at predetermined points along a preprogrammed flight path. The images are digitized and compared to stored scenes of the same locations. Differences between the two scenes are converted into a position error used to correct vehicle heading. Alternatively, image sensors can be used in man-in-the-loop guidance where the image of the target area is relayed to a person who actually flies the vehicle. The operator can either guide the UAV to impact or lock the missile on the target after which the missile homes autonomously to impact.

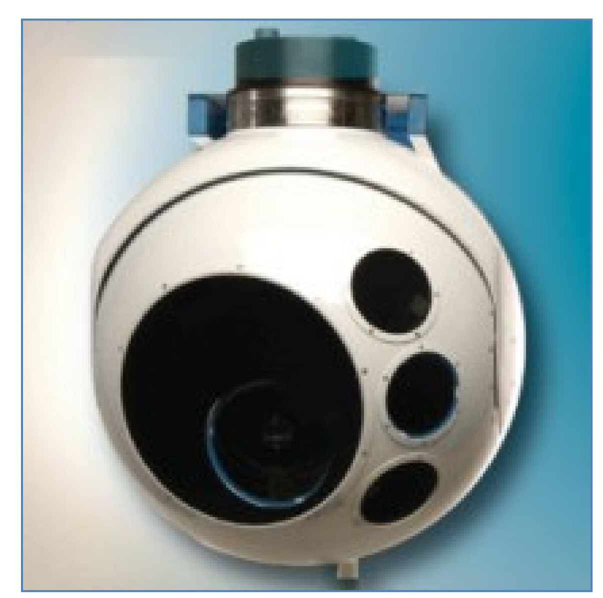


Figure 100: A passive imaging sensor is a high-performance UAV infrared system that can accommodate up to six sensors. (Northrop Grumman)

Typical Missile-Related Uses: Inertial guidance systems updated by imaging systems can be used to guide cruise missiles with extraordinary accuracy or for terminal guidance of ballistic missiles. Direction finding equipment can be used to guide UAVs, including cruise missiles, and for ballistic missile terminal guidance.

Other Uses: Direction-finding systems are used in aircraft, ships, and land vehicles. Image sensors are used in many tactical military systems for ordnance delivery, particularly from aircraft. Imaging sensor technology (sensors and algorithms) is also used extensively in robotics and photography. Imaging systems built for cruise missiles, however, usually have no commercial applications.

Appearance (as manufactured): Direction finders consist of three assemblies: an antenna or antenna array, a receiver, and processing equipment. The

antenna is a forward-looking parabolic dish, or a flat panel such as a phased array, usually mounted on a gimbaled assembly and sized for installation in the vehicle structure. The receiver is a small, low power assembly with connectors for power and signal outputs, and one or more coaxial antenna connectors. The signal processing equipment can be integral to other electronics or resident in its own electronics box. The appearance of such signal processing electronics varies greatly and may reflect manufacturer preferences rather than the functional purpose of the equipment. The size of the signal processing equipment ranges from a few centimeters to tens of centimeters on a side.

Imaging sensors consist of a lens and a visible or IR sensor, or camera. They are used with an electronic assembly consisting of a power supply and control and processing electronics, as shown in Figure 99. Another IR camera is shown in Figure 100. Visible-light sensors are recognizable by the optical lens or window. The optical port of IR light sensors may appear metallic. The flash unit has a large optical window covering a reflector and glass tube.

Imaging sensors may be either fixed or movable, and they may be mounted separately from the rest of the terrain-mapping equipment. The optics mounting features and supporting structure are robust in order to maintain stability and accuracy in the presence of large accelerations during launch, turbulence, and maneuvering. The surface of the unit close to the lens may be shaped to fit the contour of the bottom of the missile because the lens must look at the ground during flight.

Appearance (as packaged): The antennas and optical elements may have special protective packaging because of their sensitivity to shock. These elements are sealed in airtight, moisture-proof enclosures and shipped in cushioned containers. In turn, these packages are shipped in a variety of containers, including metal drums, wooden boxes, or specialized composite or metal cases.

11.A.3. Receiving equipment for Global Navigation Satellite Systems (GNSS; e.g. GPS, GLONASS or Galileo), having any of the following characteristics, and specially designed components therefor:

a. Designed or modified for use in systems specified in 1.A.; or

b. Designed or modified for airborne applications and having any of the following:

1. Capable of providing navigation information at speeds in excess of 600 m/s;
2. Employing decryption, designed or modified for military or governmental services, to gain access to GNSS secure signal/data; or
3. Being specially designed to employ anti-jam features (e.g. null steering antenna or electronically steerable antenna) to function in an environment of active or passive countermeasures.

Note:

11.A.3.b.2. and 11.A.3.b.3. do not control equipment designed for commercial, civil or 'Safety of Life' (e.g. data integrity, flight safety) GNSS services.

- China
- France
- Germany
- Israel
- Japan
- Russian Federation
- South Africa
- United Kingdom
- United States

Global production



Nature and Purpose: GNSS receivers are small electronic units with power and antenna connections used to provide very accurate vehicle position and velocity information. GNSS receivers are one of three core GNSS components, the others being satellites orbiting the earth, and ground control and monitoring stations. The GLONASS, the Global Positioning System (GPS), and Galileo are examples of GNSS, all based on a constellation of active satellites which continuously transmit signals to receivers on earth.

Method of Operation: GPS receivers detect radio signals transmitted from GPS satellites orbiting the earth in precisely known orbits. These radio signals identify the satellite and contain an accurate time reference. The receiver determines its position and velocity by measuring the signal delay among four or more satellites simultaneously and calculating the results on the basis of their locations and other information contained in the signal. GLONASS and Galileo operate in much the same way as GPS. Combined GPS/GLONASS/Galileo receivers may also be used.

Typical Missile-Related Uses: Military-grade and commercially available GNSS receivers designed or modified for the systems described in 1.A. are used in integrated flight instrument systems or sophisticated integrated navigation systems to provide very accurate positioning, navigation and timing (PNT) solutions to UAVs, including cruise missiles. Specially designed receivers can also be used in rocket systems to supplement or update the guidance set and increase accuracy.

Other Uses: Although the GPS system was originally designed for military purposes, GNSS receivers have a range of applications. GNSS receivers are used in commercial aviation and other transportation systems,

disaster relief and emergency services, surveying and mapping.



Figure 101: This GPS-inertial navigation system is designed to provide reliable and accurate positioning, navigation and timing (PNT) for critical launch and re-entry vehicles. (Northrop Grumman)

Appearance (as manufactured): GNSS receivers are small, often just a few centimeters on a side, and quite light, often weighing less than 1 kg (Figure 102). GNSS receivers of MTCR concern cannot always be visually distinguished from uncontrolled GNSS receivers because the altitude and velocity limits are implemented in firmware within the microcircuits. Determination of whether a given GNSS receiver is MTCR-controlled is best made on the basis of the receiver model, serial number, and associated documentation. GNSS receivers are also available as part of a complete guidance package, as shown in Figure 101.

Appearance (as packaged): Packaging is typical for small, expensive electronics items. These elements are sealed in airtight, moisture-proof enclosures and shipped in cushioned containers. In turn, these packages are shipped in a variety of containers, including metal drums, wooden boxes, or specialized composite or metal cases.





Figure 102: *Left:* a Global Positioning System receiver/processor unit with its patch antenna. (Sextant Avionique) *Right:* a Global Positioning System receiver/processor unit. (Litton Guidance & Control Systems)

11.A.4. Electronic assemblies and components, designed or modified for use in the systems specified in 1.A. or 19.A. and specially designed for military use and operation at temperatures in excess of 125°C.

Nature and Purpose: The limited space on rocket systems and UAV systems requires the design and manufacture of small yet very capable (high power and density) systems. If the electronics can be designed to withstand high temperatures, then weight from materials otherwise required for cooling can be avoided. Electronic assemblies and components used in such situations result from extensive design and testing efforts to ensure reliability when used in high-temperature environments. The underlying purpose of rugged, heat-tolerant electronic items is to ensure weapons system performance and reliability while minimizing weight and space.

Specialized equipment provides enhanced navigation performance to existing airframes.

Terrain-contour-mapping equipment (TERCOM) combines radar altimeter measurements with digitized terrain mapping data installed in the missile guidance system.

Scene mapping and correlation use optical sensors to gather terrain information that is then compared with digital imagery stored in the flight computer.

Doppler navigation radar equipment uses the Doppler Effect to track ground features at periodic rates to determine the velocity of the airframe, including side drift. Often, Doppler radar information is used to update inertial navigation information to the guidance computer.

Passive interferometer equipment utilizes a digital scene matching area correlator (DSMAC) to allow a UAV to navigate to its target by comparing images captured by a video camera in the flight vehicle with digitized gray scale images stored in the flight computer. Because of memory limitations in the flight computer, only images of the immediate target are stored. This system is activated once the primary guidance system navigates the UAV to the target area.

Imaging sensor equipment can be divided into two categories, active and passive. Active imaging sensors require a signal emitted by the sensor to operate. Active sensors receive and process the reflected signals. Examples of active imaging sensor equipment include synthetic aperture radars (SAR) or imaging laser radars. Passive imaging sensors receive signals emitted or reflected by objects in the environment. Examples of passive imaging sensors include optical arrays sensitive to the visible, infrared or ultraviolet spectra. In most cases, the data from imaging sensors is used to correct guidance errors by correlating the image with pre-stored target images and feeding position errors back to the guidance and control software.

Method of Operation: Military electronic assemblies and components typically run on batteries and operate much like other electronics. However, a greater margin against failure is designed into them, and their improved reliability has been confirmed by temperature-cycle testing and accelerated-age testing.

Typical Missile-Related Uses: Heat-tolerant electronics are used in guidance computers, inertial navigation systems, and re-entry vehicles in ballistic missiles. They are also useful in radars, computers, and seeker systems on UAV systems.

Other Uses: Electronic assemblies and components have virtually unlimited uses in all types of military aircraft and other military systems. The same types of assemblies with similar specifications are often used in commercial aircraft and marine vessels.

Appearance (as manufactured): Electronic assemblies are usually small and lightweight, measuring a few centimeters in length on a side and a few grams in weight. The components of these assemblies resemble those used in a wide variety of commercial applications. However, electronic assemblies used in military applications are often hermetically sealed in metal or ceramic cases, not in the transparent plastic digital image processors (DIPs) used to contain commercial assemblies. Exceptions are high-performance processors such as the quad digital signal processor (DSP) (Figure 6) in a multi-chip module package, which include stacked, high-density memory chips for exceptional speed and memory capacity. The presence of such high cost devices suggests a possible military use; however, some assemblies may look more conventional such as that shown in Figure 5.

Electronic assemblies for military use are often designed to dissipate heat. In some assemblies, the integral heat sinks are supplemented by water cooling. Cable interfaces feature rugged circular connectors or small bolt-on connectors with shielded cables. The electronics are typically mounted within an outer radio frequency (RF) shield (Faraday cage), which may be hermetically sealed or vented to the ambient pressure. Pressurized vessels are sometimes used for rockets and UAVs which must operate at high altitude in order to help conduct heat to the case and the heat sink mounting. Cases are made mainly of aluminum, with exposed metal surfaces painted or treated with corrosion-resistant materials such as nickel plating.

Appearance (as packaged): Electronic assemblies and components are usually shipped in plastic bags marked to designate an electrostatic sensitive device, cushioned in rubber foam or bubble wrap for shock protection, and shipped inside cardboard boxes or, for loads over 20 kg, wooden crates.

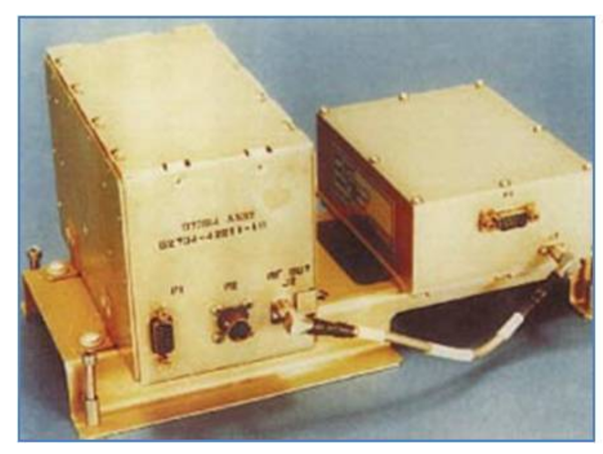


Figure 103: a UAV electronics box. (AAI Corporation)



Figure 104: Digital signal processor with the lid removed. The size is 5 cm to 7.5 cm on each side. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))

11.A.5. Umbilical and interstage electronic connectors specially designed for systems specified in 1.A.1. or 19.A.1.

Technical Note:

Interstage connectors referred to in 11.A.5. also include electrical connectors installed between systems specified in 1.A.1. or 19.A.1. and their "payload".:

- Germany
- Russia
- United States

Global production



Nature and Purpose: Umbilical and interstage electrical connectors are used to connect the missile stages, guidance system, and payload together and the rocket to the launcher. The umbilical and interstage electrical connectors may provide launch coding information, state of health, and necessary cooling fluids for the guidance system.

Method of Operation: Umbilicals connect a rocket to ground support equipment on the launch pad, silo, or erector/launcher. The umbilicals are held in place mechanically and released just prior to launch by the means of an actuator. This actuator may be spring loaded or activated by an exploding squib that will mechanically separate the umbilical or connector from the delivery system. Other umbilicals are released by the forward motion of the vehicle during launch and retracted out of the launch envelope to ensure the umbilical does not strike the rocket.

Typical Missile-Related Uses: Umbilical and interstage connectors provide a path for rockets to receive information and as a means to monitor and interrogate the system.

Other Uses: N/A

Appearance (as manufactured): Depending on the type of interstage electrical connector it will have numerous pins or sockets and most connectors will have a locking collar. Umbilicals will have a flat face, normally made of an epoxy resin or hard plastic. The face of the umbilical may have both pins and sockets and may also have connectors for liquid cooling of the guidance system.

Appearance (as packaged): Umbilical heads and interstage electrical connectors will be wrapped in anti-static shock plastic, normally gray or pink in color. Due to the numerous wires the umbilical or interstage electrical connectors may contain they will be packaged with consideration for bend radius protection. To prevent damage to these wires the cable will most likely be wrapped in a wide circle.

11.B. Test and Production Equipment

None.

11.C. Materials

None.

11.D. Software

11.D.1. "Software" specially designed or modified for the "use" of equipment specified in 11.A.1., 11.A.2. or 11.A.4.

Nature and Purpose: UAV radar, laser and IR laser radar systems use software to interpret and translate reflected signals into reconnaissance, target homing or guidance information (using terrain-matching techniques). Direction-finding equipment uses navigation software to determine (upon receipt of two or more navigation beacons) a vehicle's location and heading. Automated navigation systems can use this equipment and preprogrammed flight plans to guide a flight vehicle to its target area. Imaging sensors may then use terrain-mapping techniques to guide it or its weapon to its target. Doppler radar systems are used in UAVs to determine velocity and may be used in ballistic missiles if the Doppler systems can receive enough reflected energy.

Method of Operation: The avionics suite of sensors, integrators and computers form a series of redundant systems that result in highly accurate cruise missile navigation. Each of these sensors collect specific information from active ground signals (homing beacons) and passive sources (radar reflections from known, charted objects) and provide navigation signals to a flight computer that augments inertial guidance system sources. Missile guidance software is used to interpret this sensor data and decide what corrections to the missile flight path are required. These software functions are all integral to the onboard flight program.

Typical Missile-Related Uses: These devices are used to support UAV system and ballistic missile navigation.

Other Uses: Radar, laser systems and direction-finding equipment are all used in civil and military aircraft to augment inertial navigation systems.

Appearance (as manufactured): Typically radar system software, software used with passive sensors and flight software suitable for 1.A. systems take the form of computer programs stored on printed, magnetic, optical or other media. Any common media—including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents—can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

11.D.2. "Software" specially designed for the "use" of equipment specified in 11.A.3.

Nature and Purpose: GNSS software processes satellite signals into position information that is then used in the guidance systems of rocket or UAV systems. Processing may also include the decrypting algorithms that allow the receiver to gain access to more accurate military positioning information.

Method of Operation: Ruggedized GNSS receivers may be installed in rocket or UAV systems. GNSS software solves algorithms involving these signals and derives accurate position and velocity information. This software is usually an integral part of the onboard flight software.

Typical Missile-Related Uses: The GNSS receiver may be used to augment inertial instrument-provided position and velocity data, or it may serve as the primary source for this information.

Other Uses: GNSS software is specialized and is designed to operate within specific GNSS receivers. Civilian grade (less accurate) systems could be upgraded to military compliant systems (position accuracy <6 meters in any direction, more accurate velocity information) by decoding the more precise satellite timing information available from new civilian GPS signals that are slowly coming online as part of the GPS Modernization Program. New satellites began broadcasting the new civilian GPS signals in April 2014, the GPS Modernization Program is expected to have all the new civilian signals on 24 GPS satellites by the late 2020s.

Appearance (as manufactured): Typically GNSS software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media – including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents – can contain this software and data. GPS receivers of MTCR concern cannot always be visually distinguished from uncontrolled GPS receivers because the altitude and velocity algorithms are implemented in firmware or software.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

11.E. Technology

11.E.1. Design "technology" for protection of avionics and electrical subsystems against Electromagnetic Pulse (EMP) and Electromagnetic Interference (EMI) hazards from external sources, as follows:

a. Design "technology" for shielding systems;

b. Design "technology" for the configuration of hardened electrical circuits and subsystems;

c. Design "technology" for determination of hardening criteria for the above.

11.E.2. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or "software" specified in 11.A. or 11.D.

- China
- France
- Japan
- Russian Federation
- United Kingdom
- United States

Global production



Nature and Purpose: EMP and EMI technology is used to enhance the survival of systems in environments that have intense manmade RF noise, particularly RF noise caused by detonating nuclear weapons. The technology uses at least three approaches, often simultaneously: it configures sensitive circuits in order to minimize interference; it encloses circuits in conductive boxes; and it protects input/output (I/O) wires by surge-suppression devices, commonly just inside the conductive box.

Although the technology used to protect circuits from EMP and EMI is common and unremarkable, determining requirements and implementing them are difficult and sophisticated problems. Circuit topologies, suppression-device usage, weapon-effects-prediction models and criteria generation can be investigated by interactive computer programs, which receive weapon and system parameters and use them to assess threat environments such as fields and current levels.

Method of Operation: EMP and EMI protection is generally passive. RF enclosures dissipate RF energy as electrical currents in the conductive outer surface. Care is taken with lids and doors to ensure that fields

cannot leak into an enclosure; metal gaskets and screens are typically used to seal such openings. I/O suppression devices simply short electric fields to ground or provide high impedance (i.e., electrical opposition) by RF chokes and filters. However, some suppression devices like Zener diodes, transorbs, spark gaps and metal oxide varistors change their impedance at certain voltage or current levels.



Figure 105: A selection of electromagnetic interface suppression devices. (Sabritec)

Typical Missile-Related Uses: EMP and EMI design technology is used in ballistic missiles to protect the guidance set and electronic equipment in the re-entry vehicle from the EMP and EMI effects from nearby nuclear detonations. It is also used to protect pyrotechnic devices such as stage-separation systems from premature ignition. This technology can be used in UAV systems, but they generally need only be protected against lower levels of EMP and EMI encountered at considerable distance from nuclear blasts or other sources of interference.

Other Uses: EMP and EMI design technology is used in satellites, some military aircraft and some weapons systems. Similar EMI technology is used in the design of some commercial electronic systems such as shortwave radios and stereo equipment to reduce or prevent interference from other electrical devices. Surge-suppression devices for lightning strikes on power supplies and cords are another example of EMP/EMI protection.

Appearance (as manufactured): Such design technology can take the form of technical assistance, including training and consulting services. Technology can also take the form of blueprints, plans, diagrams, models, formulae, engineering designs and specifications, and manuals and instructions written or recorded on other media or devices such as disk, tape and read-only memories.

Some design technology is conveyed by the equipment itself. Assemblies are RF-shielded in metal enclosures, usually aluminum. For very lightweight applications, durable composite or rugged plastic boxes are used with a thin coating of metal for RF shielding. The coating is usually aluminum, often on the inside surface of the box. Exposed metal surfaces are often painted or treated with corrosion-resistant materials such as nickel plating. Some EMI suppression devices are shown in Figure 105. An EMI/EMP electronics module is shown in Figure 106. The electronics are protected by the aluminum perimeter that serves as an RF Faraday cage when hermetically sealed by the mating modules and cover. The aluminum surface beneath the circuit board serves as an RF partition of the internal modules. The bolt pattern for the cover is spaced every few centimeters to prevent gaps in the closure and to maintain even pressure

on an RF gasket that may be soft metal, metal-filled gasket, metal spring or wire mesh. EMI/EMP electronics may take on almost any shape to fit space constraints.

Appearance (as packaged): Technology in forms such as reports, data and criteria-generating programs may be packaged in oversized business envelopes or in ordinary computer electronic media mass distribution packages. Electronic EMP/EMI assemblies are typically shipped with rubber foam or bubble-wrap shock protection in cardboard or, if they weigh more than 20 kg, in wooden boxes. They are occasionally shipped in electrostatic-sensitive device (ESD) marked plastic bags even though they are not ESD-sensitive.

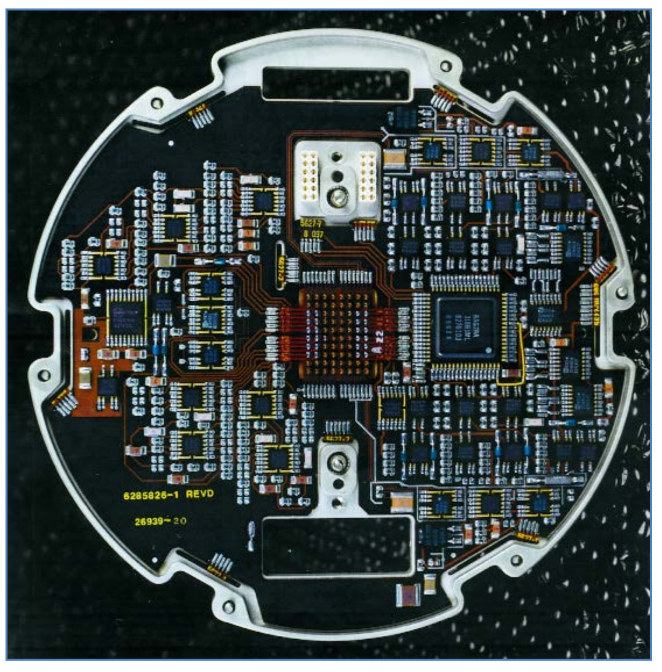


Figure 106: Electromagnetic interference / electromagnetic pulse electronics module. (Sabritec)

Category II - Item 12

Launch Support

Category II – Item 12: Launch Support

12.A. Equipment, Assemblies and Components

12.A.1. Apparatus and devices, designed or modified for the handling, control, activation and launching of the systems specified in 1.A., 19.A.1., or 19.A.2.



Figure 107: A silo liner being lifted into place for installation into a missile silo at a launch complex under construction. (The Boeing Company)

Nature and Purpose: Apparatus and devices include launch pad facilities, gantries, block houses, underground launch silos, handling equipment, systems test and check-out equipment, fueling equipment, alignment equipment and command- and-control equipment. Some of this equipment is relatively simple, such as concrete launch pads. Other items – such as the sophisticated launch pads and gantry-type launch facilities used for modern space launch vehicles (SLVs) – are far more complex. The determining factor for inclusion under 12.A.1. is whether the item is designed or modified for the systems specified in 1.A., 19.A.1., or 19.A.2.

Method of Operation: The type of equipment used during ballistic missile launching depends on the nature by which the missile is delivered to the launch site. In most approaches, the missile is delivered to the site by a truck, a train, or, at a launch pad, a dolly. The missile is then positioned either by special erectors built for the site and the missile, or by a crane attached to a permanent gantry. At silos, missiles are positioned by a crane on the transporter, which lowers the missile into the silo; alternatively, missile stages are lowered by crane or winch into the silo and assembled within the silo (Figure 107).

Complete rocket guidance systems are often aligned and calibrated by compasses and/or surveying equipment. This alignment operation may be performed initially and then regularly updated prior to launch. Many guidance systems are capable of self-alignment by sensing earth rotation. Prior to launch, target data and flight profile are loaded into the guidance system. Subsystem performance is verified by electrical and software testing equipment attached to the missile by cables. Missiles maintained on alert are verified continuously. When the status of all responses is verified as satisfactory, the vehicle is ready

for launch, and the launch sequence is executed on command. Unmanned aerial vehicles (UAVs), particularly cruise missiles, are typically designed for multiple launch platforms (with standardized interfaces).



Figure 109: A launch pad with a space shuttle on a mobile launcher platform prior to launch. (NASA)



Figure 108: Minimal launch pad with a gantry and connections to a complete rocket system. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))

Typical Missile-Related Uses: Launch support equipment is required to prepare and launch missiles. Some of these devices (guidance systems and command and control equipment) continue to monitor and control the missile throughout all or portions of the flight profile.

- Australia
- Argentina
- Brazil
- China
- France
- Germany
- India
- Iran
- Israel
- Italy
- Japan
- Netherlands
- North Korea
- Pakistan
- Russian Federation
- Republic of Korea
- Taiwan
- Sweden
- United States
- United Kingdom

Global production



Other Uses: Hydraulic systems, control electronics, computers, tanks and pipes, and communications equipment required for missile launching are similar, if not identical, to those required for numerous other purposes. Transportation, handling, erection equipment, and targeting and test algorithms are often unique to each missile, with no other uses. Silo-based launch support equipment is often unique, designed specifically for ballistic missile launch and has no commercial uses.

Appearance (as manufactured): Launch pad facilities for modern space launch vehicles (SLVs) are extremely large and complex, consisting of separate vehicle assembly buildings, large tracked vehicles (mobile launch platforms) to transport space vehicles from assembly points to the launch

pad, and fixed service towers (Figure 108).

Pads for the launch of smaller systems can have a concrete apron, a relatively small stand upon which the missile is placed, and a gantry made of steel-beams. Launch pads intended for military operations usually lack propellant storage, pumping, or handling facilities; these operations are conducted from tank and pumper trucks. They also lack permanent launch command, control, and system checkout equipment; again, these operations are conducted by equipment in trucks.

Appearance (as packaged): The sheer size of launch pads, gantries, and silos dictates that such apparatus is usually built on site and rarely shipped assembled. Consistent with their size and weight, the electronic components and consoles are wrapped and sealed in padding to protect them from shock and moisture during transport and storage, and then packed separately in boxes or crates. The electronic equipment used in some small- to medium-sized launch control shelters is often installed in the shelter, and the whole shelter is mounted on a palette for transport. Some launch support electronic equipment is portable and has been reduced to the size of a suitcase.

12.A.2. Vehicles designed or modified for the transport, handling, control, activation and launching of the systems specified in 1.A.

•Australia	•Belarus
•China	•Brazil
•France	•Egypt
•India	•Germany
•Iraq	•Iran
•Italy	•Israel
•Libya	•Japan
•Pakistan	•North Korea
•Republic of Korea	
•Syria	•Russian Federation
•United Kingdom	•Spain
•United States	•Ukraine

Global production



Nature and Purpose: Rockets and UAVs covered in Item 1.A. have been launched from trucks, trains, aircraft, ships, and submarines. With the exception of larger and more powerful UAVs capable of autonomous take-off, most rocket and missile launches (including launches from fixed sites) require vehicles, especially for transport and handling.

Vehicles modified to carry, erect, and launch missiles are distinctive because they generally have no other practical use. Some of these vehicles, referred to as Transporter-Erector-Launchers (TELs), provide a mobile launch platform independent of permanent launch facilities. Alternatively, missiles may be carried and launched from (mobile) erector-launchers (MELs or ELs), which are often towed by trucks known as prime movers. Vehicles modified to carry command-and-control equipment needed to activate, target, and control rockets or UAVs are also distinctive. Item 12.A.2. controls the vehicle, including onboard equipment, some of which would be controlled under Item 12.A.1. if removed from the vehicle.

Method of Operation: TELs and other mobile launchers perform the same preparation and launch functions as do the launch support facilities covered in Item 12.A.1. A TEL is usually loaded with its rocket or UAV by crane (which may be part of the TEL) at a staging area. The TEL transports the rocket or UAV to the launch site, where it erects it to launch position. Some missiles are fueled at this point by separate tanker and pumping trucks; others may be transported already fueled. The launch crew makes electrical connections with the vehicle and ensures that all subsystems are ready for launch. Targeting or flight plan information is loaded, and the guidance system is aligned and calibrated prior to launch.





Figure 111: ***Above***: **Eight axle MELs carrying intercontinental ballistic missiles (ICBMs; foreground) and four axle TELs carrying intermediate range ballistic missiles (IRBMs). (Via Chinese Internet)**

Figure 112: ***Top right***: **A surface launched cruise missile carrier. (Via Chinese Internet)**



Figure 110: ***Right***: **A ground control vehicle (vehicle, left) is capable of handling a range of UAV systems. (AAI Corporation)**

Typical Missile-Related Uses: Complete rocket systems and UAVs require vehicles designed or modified for the system, such as TELs and/or associated command-and-control and support vehicles.

Other Uses: These vehicles, their hydraulic systems, control electronics, and computers and communications equipment, are generally derived from a wide variety of commercial and military equipment.

Appearance (as manufactured): The distinguishing feature of TELs designed for ballistic missiles is the presence of an erection mechanism capable of lifting the missile to a vertical position. The vehicle may be tracked, but most are large vehicles about the size of a tractor-trailer or lorry, with 3 to 8 axles and rubber tires. Examples of these types of vehicles are shown in Figure 110.

TELs or MELs designed for UAVs are characterized by their relative simplicity and the presence of a launch structure (such as a rail or canister), which is sometimes inclined for launch. The launch structure can vary greatly in size and weight, depending on the UAVs to be launched. Launch structures can be as small as 2 to 3 m for hydraulic-assisted or rocket-assisted launchers of UAVs. Similar launch structures may be mounted on a tracked or wheeled vehicle (Figure 111). An example of a command-and-control truck that might accompany TELs and MELs is shown in Figure 112.

Appearance (as packaged): The launch rails and erection mechanisms used on TELs or MELs are generally integrated into the vehicle or trailer chassis. As a result, these devices are placed in their normal stowed position on the mobile vehicle or trailer when packaged for shipment from the production facility. The vehicles are driven, towed, or shipped by rail to the user facility. Other vehicles will be packaged similarly to other military or commercial vehicles.





Figure 113: ***Left***: **an erector launcher detached from its prime mover. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005)).** ***Top right***: **a transporter erector launcher for a large, Category II cruise missile. (MTCR Equipment, Software and Technology Handbook Third Addition (May 2005)).** ***Bottom Right***: **Erector launcher for a rocket-assisted UAV and its associated command-and-control van. (Teledyne Ryan Aeronautical)**




Figure 114: A pneumatic UAV launcher. Right: Command-and-control vehicles suitable for launching missiles from fixed or mobile locations. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))

12.A.3. Gravity meters (gravimeters), or gravity gradiometers, designed or modified for airborne or marine use, usable for systems specified in 1.A., as follows, and specially designed components therefor:

a. Gravity meters having all the following:

1. A static or operational accuracy equal to or less (better) than 0.7 milligal (mgal); and
2. A time to steady-state registration of two minutes or less;

b. Gravity gradiometers.

- *Relative Gravity Meters*
  - Canada
  - China
  - Germany
  - Russian Federation
  - United States
- *Gravity Gradiometers*
  - United States

Global production



Nature and Purpose: Since the earth is not a perfect sphere, its gravitational field strength fluctuates across its surface. Changes in topography, elevation, latitude and subterranean density can affect the force of gravity. Gravity meters and gravity gradiometers make very accurate measurements of the magnitude of the force of gravity at various locations. These data are used to create detailed maps of the earth's gravitational field for several kilometers around a ballistic missile launch site because local variations in gravity can cause inaccuracies in inertial guidance unless accounted for in the missile guidance software. Airplanes, helicopters, ships, and submarines outfitted with gravity meters can make gravity maps at sea. Airplanes and helicopters outfitted with gravity meters can make gravity maps over mountainous terrain. Gravity gradiometers can also be used as sensors in guidance systems to improve accuracy.

Method of Operation: The methods of operation vary with the different types of equipment. Some accurately measure the fall time of a dropped mass; others use a set of pendulous electromagnetic force rebalance accelerometers that rotate on a carousel. Some are operated with the airplane, ship, or submarine in motion, and others are lowered to the surface of the land or sea floor to take a measurement. Systems designed to operate on a moving platform such as a ship or airplane need inertial navigation quality gyros and accelerometers for two-axis stabilization of the sensor platform. Systems designed to be lowered to the surface of the land or sea floor need only be self-leveling.

Gravity gradiometers use a set of very high quality accelerometers on a precision rotating turntable. As the accelerometers rotate in a horizontal plane, they detect the subtle gravity differences about the perimeter of the turntable. The difference between the average readings taken on the east and west sides of the turntable, divided by the diameter of the turntable, yields the longitudinal gravity gradient.

Similarly, the difference between the average readings taken on the north and south sides of the turntable, divided by the diameter of the turntable, yields the latitudinal gravity gradient. Use of multiple accelerometers reduces the effect of individual accelerometer scale factor drift, and rotating the accelerometers about the perimeter virtually eliminates the effect of bias drift.



Figure 115: This automated gravity meter is one of the most precise, rugged and lightweight gravity meters. Under normal conditions, it can be leveled for mGal readings within 30 seconds, and has a drift rate of less than 0.5 mGals per month. (ZLS Corporation)

Typical Missile-Related Uses: Gravity maps for several to hundreds of kilometers in the area of ballistic missile launch sites are required for highly accurate systems. Airborne gravity meters can be used to map a large area of rough terrain or open sea adjacent to mountain roads or other areas where mobile missiles might operate. Ship or submarine-borne gravity meters are used to map the gravitational attraction beneath the sea to facilitate increased accuracy of ballistic missiles launched from submarines or from land installations near the coast. Because the effects of gravity variations in the launch area are rather small, gravity maps are primarily useful for ballistic missile systems that are already very accurate. Gravity gradiometers may be useful for UAV guidance, perhaps over water or other featureless terrain.

Other Uses: Gravity meters and gravity gradiometers are used in petroleum and mineral resource exploration, civil engineering, geophysical mapping, geotechnical and archaeological exploration, groundwater and environmental studies, tectonic research, volcanology research, and geothermal research. Gravity gradiometers are used as navigation aids on submarines.

Appearance (as manufactured): Gravity meters and gravity gradiometers are high quality, sensitive electronic and mechanical instruments. Gravity meter appearance ranges widely because companies build them differently for different purposes. Systems fully integrated into a single case may be as small as 25 cm x 32 cm x 32 cm and weigh as little as 6 kg (with battery) (Figure 115). Systems with separate cases may be as large as a cubic meter and weigh 350 kg; these large systems are modular and may be packaged in more than one container for shipping. The sensor unit of air-sea gravity meters – designed specifically for marine and airborne applications (Figure 116) – is difficult to specify since it is dependent on the characteristics of the vessel, the conditions at sea, and navigational accuracy (typically around 1 mGal). Systems such as these are MTCR controlled if they meet the performance criteria specified in Item 12.A.3.



Figure 116: A dynamic meter; the full digital control system of the meter enhances overall system accuracy by eliminating gain and offset drifts inherent in analogue electronics. (ZLS Corporation)

Electronic and mechanical components are enclosed in either hard plastic or metal cases. Some systems have the instrument and control panel contained in the same case; other systems have the instruments separated from the control panels. The cases typically have visible

electronic or mechanical control panels, pads, rotating control knobs, toggle- and push- switches, and connections for external electronic and computer cables.

Some have screens for observing the data collected in either digital or analog form; some have ports for printing hard copies of the data. Most have removable access panels. Batteries may be supplied to operate the system. Some systems have built-in computers and software. Some gravity meters are built to be lowered by a cable to the ground and operated from a helicopter. Others are built to be lowered to the sea floor by a ship or submarine.

Appearance (as packaged): Because the systems are very sensitive and expensive, they are packaged and shipped in rigid containers, which include formed plastic, plastic popcorn, plastic bubble wrap, or other materials designed to protect them from shock. The shipping containers usually have warning labels such as 'fragile', 'handle with care', or 'sensitive instruments'.

12.A.4. Telemetry and telecontrol equipment, including ground equipment, designed or modified for systems specified in 1.A., 19.A.1. or 19.A.2.

Notes:
1. 12.A.4. does not control equipment designed or modified for manned aircraft or satellites.
2.12.A.4. does not control ground based equipment designed or modified for terrestrial or marine applications.
3.12.A.4. does not control equipment designed for commercial, civil or 'Safety of Life' (e.g. data integrity, flight safety) GNSS services.

- China
- France
- India
- Russian Federation
- United Kingdom
- United States

Global commercial production



Nature and Purpose: Telemetry equipment involves sensors, transmitters, and receivers that send in-flight information on rocket or UAV performance to the ground. These devices allow engineers to monitor a vehicle's flight and performance, and determine the causes of any failure. Such equipment is used extensively during rocket and UAV flight testing. During flight tests, telemetry is normally collected throughout the entire flight. Telecontrol equipment that uses various sensors, receivers, and transmitters may be used to remotely control rockets or UAVs during powered flight. However, many operational ballistic missiles and cruise missiles fly autonomously (that is, without any telecontrol).

Method of Operation: Telemetry equipment installed in developmental rockets and UAVs monitor the important flight parameters (acceleration, vibration, control surface settings, pressures, temperatures, flow rates, valve positions, power/voltage, etc.) and transmit these data to one or more ground stations. The receiver decodes the data, displays them, and

records them for playback and analysis later. Most operations are set up inside a building with an external antenna connection. If gimbaled, this antenna can pivot in three axes to track the rocket system or UAV in flight. Many ground stations, either fixed or mobile, may be required along the flight path.



Figure 117: Some telemetry transmitters are designed to withstand harsh operating environments requiring compact and rugged package. (AMP)

Typical telecontrol systems are different for rocket and UAV systems. Rockets using command guidance are usually tracked by radar near the launch site. Flight path data are processed to compare the actual and desired trajectory. If deviations occur, steering commands are sent from the ground station by radio to a receiver in the rocket system, which implements the commands to bring it on track. This command loop is maintained until the engines are turned off; the rest of the flight is ballistic unless the missile uses aerodynamic control surfaces. Telecontrol for UAV systems is often implemented by a "man-in-the-loop" concept. A sensor (such as a TV) in the UAV transmits a visual image to the ground control station. A human pilot views this image and sends steering commands to the vehicle over the data link.


Figure 118: A Large telemetry antenna system designed for UAVs and flight test centers. (Chelton Antennas)

Typical Missile-Related Uses: Telemetering is important in the verification of performance during flight tests for both rockets and UAVs. Without such data, flight testing can be lengthy and expensive requiring many more flight tests. Telecontrol is frequently used for UAV applications. Telecontrol is rarely used in operational ballistic or cruise missiles that carry weapons because the data link is vulnerable to jamming or disruption.

Other Uses: Similar telemetry equipment is used to test commercial and military aircraft. It is also used in industry to collect data from remote sites and from chemical or other plants with a hazardous environment. It is also used in robotic land vehicles that must operate in hazardous environments.

Appearance (as manufactured): Telemetering equipment installed on flight vehicles is contained in small metal boxes with power, cable, and antenna connections, and have few distinctive features (Figure 117). The most visible telemetering equipment at the ground station is the telemetry receiving antenna. They are often large parabolic dishes that can rotate in two dimensions, as shown in Figure 118 (sometimes as large as a 60 ft dish mounted on a 38 ft high steel tower). Electronic equipment used at the ground station to demodulate, read, record, interpret, and display the telemetry looks like most rack-


Figure 119: A large SATCOM military antenna designed for major command posts and mobile command posts, and suitable for communications with UAVs. (General Dynamics)

mounted scientific equipment or computers with few distinguishing features.

Telecontrol equipment installed in UAVs permits communication between the UAV and the ground control station. Like telemetry equipment, this equipment is housed in metal boxes with power, cabling, and antenna connections, all unremarkable in appearance. Some UAVs communicate to their ground control stations by way of satellites and require special ground-based SATCOM antennas (Figure 119).

Appearance (as packaged): Because of the sensitivity of the electronics, telemetry equipment is usually shipped in cushioned cardboard or wooden containers. Some containers may have labels indicating the need for careful handling. Usually the equipment is sealed in plastic to protect the electronics from moisture and electrostatic discharges. Large assemblies of equipment such as integrated telecontrol stations will be disassembled and shipped in separate containers.



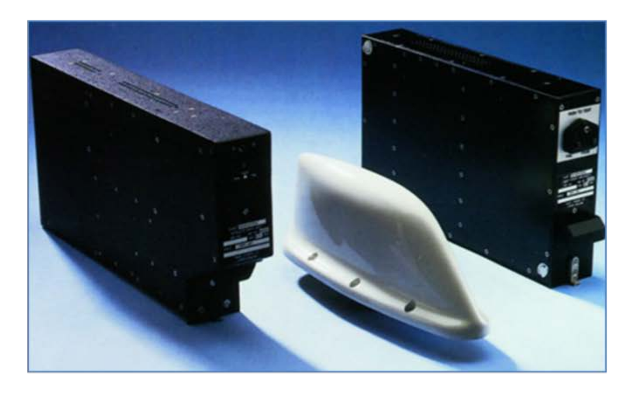






Figure 120: *Top left*: A SATCOM antenna installed in a UAV (General Atomics Aeronautical). *Top right*: A commercial satellite transceiver with streamlined antenna. (Racal Avionics). *Bottom right*: A portable flight controller console for a UAV (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005)). *Bottom left*: A commercial system with a mechanically steered antenna (streamlining not shown. (Racal Avionics)



Figure 121: Representative ground-station telemetry receiving and processing equipment. (In-Snec)

12.A.5. Precision tracking systems, usable for systems specified in 1.A., 19.A.1. or 19.A.2. as follows:
a. Tracking systems which use a code translator installed on the rocket or unmanned aerial vehicle in conjunction with either surface or airborne references or navigation satellite systems to provide real-time measurements of in-flight position and velocity;
b. Range instrumentation radars including associated optical/infrared trackers with all of the following capabilities:
1. Angular resolution better than 1.5 mrad;
2. Range of 30 km or greater with a range resolution better than 10 m rms; and
3. Velocity resolution better than 3 m/s.

- China
- France
- Germany
- Israel
- India
- Japan
- Pakistan
- Russian Federation
- South Africa
- Switzerland
- United Kingdom
- United States

Global production



Nature and Purpose: Precision tracking systems produce accurate records of rocket system trajectory or UAV system flight path. Engineers use these data to help determine vehicle performance and the causes of any vehicle failure. Range safety engineers also use these data to monitor the missile flight path. If the missile veers into an unsafe trajectory, it is destroyed. Precision tracking systems can be used in conjunction with, or as an alternative to, telemetry equipment, which sends back data on vehicle acceleration time history, from which missile trajectory can be reconstructed.

Method of Operation: Code translators installed on a rocket or UAV process signals received from ground or satellite transmitters. Those signals carry timing data that allow the code translator to determine the distance to each transmitter. These data are sent back to the ground station on a different downlink frequency. Because the transmitters are in known locations, the ground station can accurately determine missile position and velocity. These data can be displayed in real time or recorded.

Range instrumentation radars are also used to determine missile position and velocity. Usually a radar with a wide field-of-view is used to track the approximate vehicle location, which is then used to aim radars with a narrow field-of-view, optical trackers, or infrared trackers capable of determining missile angle, range, and velocity with the required precision. These data are recorded as they occur, along with an ongoing record of the time. A variation on this approach is to install in the flight vehicle a small transmitter that broadcasts or a transponder that receives and re-broadcasts at the radar operating frequency and thereby provides a beacon that allows the radar to track the vehicle more easily.

No matter how the data are collected, to be useful, information on time and position must be interpreted. Post-flight data processing may take place anywhere, but it is often conducted in the telemetry data processing center where real-time data are received and recorded. These recorded data are read, filtered, and processed. The processed tracking data are then re-recorded on disk or tape for further analysis or output plotting.

Typical Missile-Related Uses: Precision tracking systems and range instrumentation radars are helpful during the testing phase of the flight program to determine whether the missile is traveling along the predicted trajectory and to monitor missile flight for any anomalies. Such information is used to evaluate and improve the performance of numerous subsystems. The software that processes post-flight recorded data and thereby helps determine vehicle position throughout missile flight path is essential to interpretation of those flight data.



Figure 124: A mobile phased-array missile tracking radar. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))



Figure 123: A mobile laser missile-tracking system. (Contraves)



Figure 122: An electro-optical laser tracking system. (BAE Systems)

Other Uses: These systems can be used to support commercial and military aircraft testing and the development of weapons, including artillery and small rockets. Industry uses post-processing of data to evaluate events after the fact, such as race car performance.

Appearance (as manufactured): Precision tracking systems and range instrumentation radars look like ground-based portions of telemetering and telecontrol equipment. They include familiar dish-type radars as shown in Figure 118 and Figure 119, as well as phased-array radars, which are characterized by their flat (rather than concave) surface (Figure 124). Also used are optical devices that look like telescopes, large robotic binoculars and laser tracking systems that resemble optical instruments (Figure 122 & Figure 123).

The precision tracking system hardware (transponders) carried aboard rockets or UAVs are generally very small electronics enclosures that vary from 800 cm^3 to 2,500 cm^3. They are generally solid, environmentally sealed enclosures with external power and antenna connectors. The only sub-element of these transponders is the antenna element, which is normally located on the external surface of the rocket or UAV.

Appearance (as packaged): Because of its sensitivity to shock, the electronic equipment is usually shipped in cushioned containers. Some may have labels indicating the need for careful handling. This equipment is usually sealed in plastic to protect it from moisture and electrostatic discharge. The larger radars, optical trackers, and laser trackers are shipped disassembled in wooden crates and assembled onsite and all optics are protected with environmental covers.

12.A.6. Thermal batteries designed or modified for the systems specified in 1.A., 19.A.1. or 19.A.2.

Note:
Item 12.A.6. does not control thermal batteries specially designed for rocket systems or unmanned aerial vehicles that are not capable of a "range" equal to or greater than 300 km.

Technical Note:
Thermal batteries are single use batteries that contain a solid non-conducting inorganic salt as the electrolyte. These batteries incorporate a pyrolytic material that, when ignited, melts the electrolyte and activates the battery.

- China
- France
- Germany
- India
- Israel
- United Kingdom
- United States

Global production



Nature and Purpose: Correct battery function is a crucial component in meeting the mission requirements of complete delivery systems. Thermal batteries, which are self-contained, hermetically sealed, electrochemical power sources, have a number of characteristics that make them especially resistant to harsh operating environments, and as such they are very well suited to meet the demands of many military requirements. These characteristics include: a capacity to remain dormant with a long shelf life of greater than 20 years, without degradation in performance and at the same time retaining the ability to activate and discharge their power instantaneously; performance at extreme temperatures (ranging from -65 °F to +221 °F); high current density for high power applications; high reliability; and low maintenance and storage costs.



Figure 125: A thermal battery. (ASB Group)

Method of Operation: Thermal batteries are composed of a series of cells (known as the cell stack), each having an anode, electrolyte, cathode and heating mass. The electrolyte remains solid until activation, and the cells remain completely inert during battery storage. This property of inactivated storage has the double benefit of avoiding deterioration of the active materials during storage, while at the same time eliminating the loss of capacity due to self-discharge until the battery is called into use.

There are two types of thermal battery design that provide varying mechanisms for battery activation. One uses a fuse strip along the edge of heat pellets to initiate heating of the electrolyte. The fuse strip is typically fired by an electrical igniter by applying an electric current through it. The second design uses a center hole in the middle of the battery stack into which the high-energy electrical igniter fires a mixture of hot gases and incandescent particles. The latter design allows much faster activation times (tens of milliseconds vs. hundreds of milliseconds for the edge-strip design). Battery activation can also be accomplished by a percussion primer, similar to that used in small arms ammunition.

Typical Missile-Related Uses: Thermal batteries are used in applications that require the immediate delivery of high power, such as providing power to the electrical activation systems in space launch vehicle systems and missiles, powering electronically operated guidance systems in missiles, or air defense and telemetry systems. They are the primary source of electrical power for a range of missiles as well as nuclear weapons. The growing electricity requirements in these systems due to increasing electronic functionality in advanced and modern missiles will increase the demand for thermal batteries in these types of applications.



Figure 126: A selection of thermal batteries designed for a range of military applications. (HBL Power Systems)

Other Uses: Thermal Batteries have utility in a range of other applications, both military and civilian. They provide electric power for mines and guided artillery, and are also used as energy sources for industrial purposes (such as drilling platforms and surveillance systems). They also can be applied to the electric vehicle market. The main barrier to the widespread use of thermal batteries outside specific military applications is that they are economically unviable. Almost all thermal batteries are for one-time use, and rechargeable thermal batteries are highly inefficient (owing to the high energy loss due to thermal isolation and the long start-up time required to reach optimum operating temperature).

Appearance (as manufactured): Thermal Batteries are manufactured in hermetically sealed steel housings at atmospheric pressure containing either dry air or inert gas backfill. They are relatively small in size, ranging from around 3.5 cm to 17.5 cm in breadth and 6 cm to 22 cm in height. Weight ranges from around 200 g to 1.2 kg (Figure 126).

Appearance (as packaged): Thermal Batteries are shipped in metal or plastic crates or in padded cardboard boxes.

12.B. Test and Production Equipment

None.

12.C. Materials

None.

12.D. Software

12.D.1. "Software" specially designed or modified for the "use" of equipment specified in 12.A.1.

- Argentina
- Belarus
- Brazil
- Canada
- China
- France
- Germany
- Iran
- Israel
- Italy
- North Korea
- Pakistan
- Russian Federation
- South Africa
- Republic of Korea
- Sweden
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: Missile ground support and checkout software is used to monitor the readiness condition of the rocket or UAV prior to launch. This software is installed on one or more pieces of ground support equipment and may be tailored to monitor a single missile subsystem, such as the guidance system. Often, this software contains the secure codes that lock out unauthorized persons from launching the missile without proper credentials, as well as code that initiates launch and monitors terminal countdown until first-stage ignition.

Method of Operation: Ground support and checkout software is loaded in the rocket or UAV ground support equipment. This software manages ground hardware that is electrically connected to the rocket or UAV through various umbilical connections to collect missile status signals. Upon receipt of a launch order, the software may contain codes that authenticate the launch order and, if proper, initiate and monitor the rocket/UAV launch sequence. If properly designed, the software provides the operator with launch countdown status that is useful if the system malfunctions and the launch fails prior to first stage ignition. Technical analysis of the system indications will allow prompt recovery and a subsequent re-launch attempt.

Typical Missile-Related Uses: This software is used to monitor missile systems prior to launch. Other versions may be used to initiate and monitor launch until first-stage ignition.

Other Uses: N/A.

Appearance (as manufactured): Typically, missile ground support and checkout software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media—including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents—can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

12.D.2. "Software" which processes post-flight, recorded data, enabling determination of vehicle position throughout its flight path, specially designed or modified for systems specified in 1.A., 19.A.1. or 19.A.2.

- Belarus
- China
- France
- India
- Israel
- Italy
- Pakistan
- Sweden
- Russian Federation
- United Kingdom
- United States

Global production



Nature and Purpose: Post-flight data processing may take place anywhere, but it is often conducted in the telemetry data processing center, where real-time data are received and recorded. These recorded data are read, filtered and processed. The processed tracking data are then rerecorded on disk, tape, or other media for further analysis or output plotting.

The post-flight and recorded data processing software typically consists of mathematical filtering software routines that process the previously recorded data in order to provide a smooth estimate of the vehicle trajectory. This processing software is used both to provide the estimated vehicle position data for periods of time when a real-time data outage may have occurred and to perform filtering in order to get the best estimate of the trajectory. Many different types of mathematical filter implementations are used, varying from the simplest such as a straight-line interpolation between data points, to more sophisticated polynomial-based filtering such as spline-fit filtering. Some filtering routines also use Kalman filtering to post-process these data, although the Kalman filtering is normally used for real-time tracking applications because of its ability to use simplified matrix manipulations to arrive at tracking solutions.

Method of Operation: Flight-test range facilities transmit flight data and range tracking data to a central processing facility. The processing facility contains high-speed computers that convert this data and, in some instances, combine individual ground sensor and flight instrument data telemetered from the rocket or UAV to synthesize performance information.

Typical Missile-Related Uses: Flight-test data is used to support rocket system performance and accuracy evaluation. It is also used to evaluate UAV flight performance.

Other Uses: The equipment used to support rocket and UAV flight-test evaluations is also used to evaluate civil and military aircraft performance.

Appearance (as manufactured): Typically, software that processes missile post-flight, recorded information that is used to determine the test flight trajectory takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media—including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents—can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

12.D.3. "Software" specially designed or modified for the "use" of equipment specified in 12.A.4. or 12.A.5., usable for systems specified in 1.A., 19.A.1. or 19.A.2.

- Australia
- Belarus
- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Pakistan
- Russian Federation
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Global production

Nature and Purpose: Software described in this section is used to collect flight data that is broadcast to ground stations (telemetered) for analysis.

Method of Operation: This software is used to collect in-flight system and performance information (usually from the flight computer) and to compress and modulate the data into a data stream that is then broadcast to ground-based receivers. Other software in these ground stations takes the received data stream, decompresses the data, and converts them into performance information. System engineers then analyze the information to evaluate system performance.

Typical Missile-Related Uses: This software is solely designed to collect, process and display rocket or UAV flight performance information that engineers analyze to determine system performance. It is central to rocket or UAV flight-test evaluation.

Other Uses: N/A.

Appearance (as manufactured): Typically, software that collects and processes missile telemetry takes the form of a computer program stored on printed magnetic, optical or other media. Any common

media—including magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents—can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash

12.E. Technology

12.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or "software" specified in 12.A. or 12.D.

drives and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network or the internet.

Nature and Purpose: Launch support technology is knowledge or data necessary to develop and operate launch support equipment and its associated software. The purpose of launch support technology is to establish or enhance the development, production and use of launch support and checkout equipment, and to control (initiate or deny) and monitor rocket or UAV launches. Technology, in this section, includes the knowledge to operate and develop launch support equipment and its associated software as well as the ability to understand the telemetry data produced.

Method of Operation: Launch support technology is available in many forms. It may consist of instruction provided by a person or organization experienced with developing ground control and checkout or telemetry systems for rockets or UAVs who acts as a trainer in a classroom on or near the development or production site. A country may receive technical assistance on the design and development of ground support or telemetry equipment through training supplied by or in another country. Any manuals and materials received during training may qualify as technical data. A country may also receive procurement assistance for the needed technical equipment, machines or materials either by provision of the items or in the form of guidance as to what equipment should be procured.

Typical Missile-Related Uses: This technology is used primarily to develop, produce and use missile ground support and checkout software, launch control and monitor software, launch support equipment that uses this software, and to collect, transmit, receive and process missile performance information using telemetry equipment and support software.

Other Uses: N/A.

Appearance (as manufactured): N/A.

Appearance (as packaged): N/A.

Category II - Item 13

Computers

Category II – Item 13: Computers

13.A. Equipment, Assemblies and Components

13.A.1. Analogue computers, digital computers or digital differential analysers, designed or modified for use in the systems specified in 1.A., having any of the following characteristics:
a. Rated for continuous operation at temperatures from below -45°C to above plus +55°C; or
b. Designed as ruggedised or "radiation hardened".

Note:
Item 13 equipment may be exported as part of a manned aircraft or satellite or in quantities appropriate for replacement parts for manned aircraft.

•Canada	•China
•France	•Germany
•India	•Israel
•Italy	•Japan
•North Korea	•Russian Federation
•South Africa	•Republic of Korea
•Sweden	•Taiwan
•Ukraine	•United Kingdom
•United States	

Global production



Nature and Purpose: Complete rocket systems and UAVs controlled in 1.A. use at least one computer, primarily in the guidance set, integrated flight instrument system or integrated navigation system. The guidance computer calculates missile velocity and position information from onboard sensors, using the data gathered for comparison with the defined missile flight path and trajectory, and sending steering commands to correct any detected errors. Computers may also provide time references for the missile and give cut-off commands to the propulsion system and arming commands to the weapons payload at the appropriate flight times. Mission computers may also be used to store and execute preprogrammed flight profiles.

Method of Operation: Onboard analog or digital computers rapidly integrate the equations of motion for missile flight and compute the magnitude and duration of the commands necessary to maintain the missile flight path. The computers receive electrical signals from onboard sensors, perform the appropriate calculations, and send command signals to the various missile systems to try to match the preprogrammed flight path. These computer systems are usually powered by batteries (typically 28 V) and use connecting cables to interface with the sensors and control systems.

Typical Missile-Related Uses: Most complete rocket systems and UAVs (including cruise missiles) have at least one ruggedized digital computer for navigation and control computations and digital integration of Inertial Measurement Unit (IMU) data. Many also use analog computers to provide closed loop control of

analog servos for IMU gimbals and for flight control surface stabilization. The computer must be able to operate at the temperature extremes experienced by ballistic missiles traveling through space, High Altitude Long Endurance (HALE) UAVs, or cruise missiles carried on external pylons at high altitude. Missiles require ruggedized computers to handle the vibrations and shocks of missile flight, and missiles designed to survive and operate in nuclear environments require radiation-hardened computers.

Other Uses: Ruggedized computers have several military and commercial applications. Most military and civilian aircraft, tactical missiles, and spacecraft require ruggedized computers that operate within the temperature extremes defined in the MTCR Annex. Long-lifetime spacecraft and satellites stationed in or near the radiation belts also have requirements for radiation hardening, but those requirements may be somewhat lower than the Annex specification.



Figure 127: A mission computer for multiple platforms. Its compact size makes it ideal for the confined space on some UAVs. (Curtiss Wright Embedded Computing Controls)



Figure 128: Another mission computer for multiple platforms, this one is designed for use in harsh aerospace and military applications. (Curtiss Wright Embedded Computing Controls)

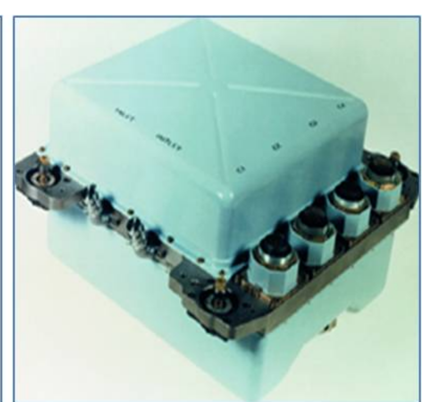


Figure 129: A radiation-hardened electronics assembly with liquid cooling. (The Charles Stark Draper Laboratory, Inc.)

Appearance (as manufactured): Computers configured for missiles and UAVs are usually housed in metal enclosures with integral heat sinks to dissipate heat generated by high operating speeds. They are also compact in size and designed to fit into space-constrained environments. Two examples of ruggedized multi-mission computers designed for aerospace and military applications are seen in Figure 127 and Figure 128. Within such assemblies are a wide variety of electronic parts that may appear to be similar to those widely used in commercial applications.

A distinguishing characteristic (although not unique to military use) is hermetically sealed metal and ceramic components as opposed to more common plastic components found in commercial electronics (Figure 129). The cable interfaces feature rugged, circular connectors or small bolt-on connectors with shielded cables. The electronics are typically within an outer radio frequency (RF) Faraday cage enclosure, which may be hermetically sealed or vented to the ambient pressure. Pressurized vessels are used to help conduct heat to the case and heat-sink mounting of missiles and UAVs, which operate at high altitude. For applications requiring lightweight assemblies, the computers can be packaged in rugged plastic containers with metal coatings inside the plastic covers for RF shielding.

Appearance (as packaged): Electronic computer assemblies and parts typically weigh less than 25 kg. They are packaged in plastic bags, placed inside cardboard boxes, and packed in rubber foam or bubble wrap shock protection; box labels typically indicate the contents as electrostatic sensitive devices. Larger units integrated into a larger system and over 25 kg may be packed in metal or wooden boxes.

13.B. Test and Production Equipment

None.

13.C. Materials

None.

13.D. Software

None.

13.E. Technology

13.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment specified in 13.A.

Nature and Purpose: The technology described in this section is that necessary to develop, produce and use ruggedized computers in rocket systems and in UAV systems, including cruise missiles.

Method of Operation: Technical assistance is available in many forms. Technical assistance may consist of instruction in a classroom on or near the development or production site and provided by a person or organization experienced in developing ruggedized computers for rocket systems or UAVs. A country may receive this technical assistance from one or more foreign entities that possess the facilities needed to provide hands-on experience to design and develop the desired technology. Assistance may also include guidance as to what parts or components to procure or help in procuring them.

Typical Missile-Related Uses: The technology included in this section is used to provide digital or analog computers designed to operate within a rocket or UAV system to complete navigation and control computations and digital integration of IMU data. Rocket systems and UAVs also use analog computers to provide closed loop control of analog servos for IMU gimbals and for flight control surface stabilization.

Appearance (as manufactured): N/A.

Appearance (as packaged): N/A.

Category II - Item 14

Analogue to Digital Converters

Category II – Item 14: Analogue to Digital Converters

14.A. Equipment, Assemblies and Components

14.A.1. Analogue-to-digital converters, usable in the systems specified in 1.A., having any of the following characteristics:

a. Designed to meet military specifications for ruggedised equipment; or

b. Designed or modified for military use and being any of the following types:

1. Analogue-to-digital converter "microcircuits", which are"radiation-hardened" or have all of the following characteristics:

a. Rated for operation in the temperature range from below -54 °C to above +125 C; and

b. Hermetically sealed; or

2. Electrical input type analogue-to-digital converter printed circuit boards or modules, having all of the following characteristics:

a. Rated for operation in the temperature range from below -45°C to above +80 °C; and

b. Incorporating "microcircuits" specified in 14.A.1.b.1.

•France	•Germany
•Israel	•Japan
•Russian Federation	•Sweden
•United Kingdom	•United States

Global production



Nature and Purpose: Analog-to-digital converters (ADCs) are electronic devices for converting an analog signal, which is a continuously varying voltage, to a digital signal, which consists of discrete voltages representing a pattern of "1s" and "0s" (binary data). These converters allow the analog outputs of various devices such as sensors, accelerometers, and gyros to be processed by digital devices, such as digital signal processors (DSPs) and computers.

Method of Operation: In its simplest form, an ADC is a voltmeter with a binary "word" as its output. The longer the word (i.e., the more "bits" per word), the more accurately the input voltage can be represented. For example, an 8-bit word representing a voltage range of zero to one volt provides 256 discrete values. With one word assigned to zero, this results in 255 increments of just over 3.92 mV each. Increments of 3.92 mV limit the theoretical accuracy to plus or minus 1.96 mV or 0.196%. Another important feature of ADCs is the conversion rate, which is a measure of how fast the device can update the output word to reflect rapid changes in the input voltage. A faster conversion rate allows the ADC to process input signals with higher frequency content. Manufacturers

use one of several different circuit design approaches (i.e. direct conversion, integrating, delta-encoded, sigma-delta, and others) to make the conversion.

Most ADCs are designed to have a linear input-to-output relationship. However, in more elaborate schemes, input voltages are mapped to digital values according to calibration data previously taken from the analog instrument to which the ADC is mated. This mapping allows the ADC to compensate for nonlinearities in the analog measurement.

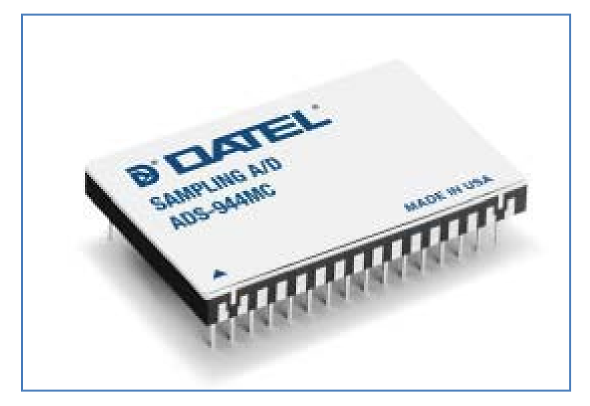


Figure 130: An analog-to-digital converter used primarily in radar signal analysis. (Datel)

Typical Missile-Related Uses: Any missile using a digital computer requires ADCs. The ADCs need to work over the temperature range specified above and be hermetically sealed if, like most ballistic missiles, they are flown exo-atmospherically.

Other Uses: ADCs are in widespread use, with ruggedized parts common in all aircraft, automobile electronic ignition systems, and engine sensors. Other commercial applications include a variety of sensor systems, electronic cameras, medical imaging systems, and radios. Spacecraft and satellites stationed in or near the radiation belts require radiation-hardened ADCs, which operate over the temperature extremes indicated. Although some space application requirements (approximately 100 krad (Si) total dose) are about five times lower than the Annex specification, such systems often use MTCR-controlled ADCs.

Appearance (as manufactured): Military ADC components are hermetically sealed metal packages in order to ensure operation in adverse environments and to dissipate the heat associated with processing data at high data rates from sensors. Aluminum is the primary metal used for ADC board frames, structures, and heat sinks. Assemblies can range from a few centimeters to about 0.3 m or more on a side and weigh from 100 g up to 25 kg. Their package density approaches one-third the density of aluminum.

Integrated ADC assemblies consist of a wide variety of electronic parts that are not readily distinguishable from those used in commercial applications. They may be populated with discrete components and resemble other military electronics (Figure 131). Military and commercial-grade discrete ADCs differ externally only in part number. Radiation-hardened ADCs are often packaged on a single printed integrated circuit (IC) board ideal for use in ballistic missiles. These devices have special design features to make them rugged and resilient to shock and vibration environments. Although ADC circuit boards are similar to those for DSPs, they include additional circuitry for buffer

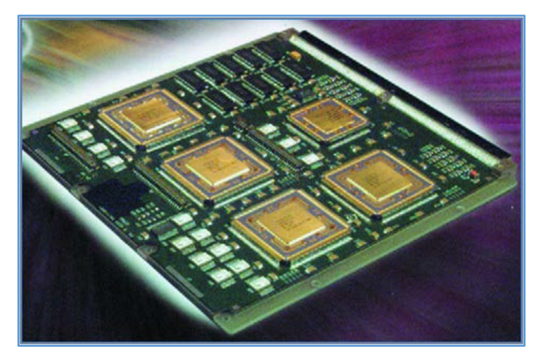


Figure 131: Typical analog--to-digital converter/digital signal processor board. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))

amplifiers, multiplexing, or signal conditioning (filters, voltage limiting, etc.) As a result, a larger portion of the ADC circuit board is made up of discrete components (resistors, capacitors, diodes, etc.) Printed circuit boards are fiberglass-epoxy with copper heat sinks and traces. Electronics parts are in special metal cases (mostly copper-nickel) with aluminum or gold bond wires and silicon substrates.

Appearance (as packaged): ADC printed circuit board assemblies and modules weigh less than 25 kg. They are encased in plastic bags that are marked to indicate electrostatic sensitive devices, and they are packed in rubber foam or bubble wrap for shock protection inside cardboard boxes.

14.B. Test and Production Equipment

None.

14.C. Materials

None.

14.D. Software

None.

14.E. Technology

14.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment specified in 14.A.

Nature and Purpose: The "technology" described in Item 14 is the knowledge and experience necessary to develop, produce and use ruggedized analog-to-digital converters (ADCs) in rocket and UAV systems, including cruise missiles. Blueprints, schematics, and engineering drawings, are considered part of the technical data for this technology.

Method of Operation: ADCs are always integrated into circuit card assemblies for missile applications. The technical assistance required to accomplish this may consist of skills such as circuit board design, circuit board layout, manufacturing, design, and testing of these assemblies. A country may receive this technical assistance from one or more foreign entities that possess the design and development facilities needed to develop the desired technology. A country may also receive procurement assistance to locate and purchase critical components.

Typical Missile-Related Uses: This technology allows the analog outputs of various devices such as sensors, accelerometers and gyros to be processed by digital devices, such as digital signal processors and flight computers.

Other Uses: ADCs are widely used in aircraft, ignition systems, and engine sensors. Other commercial applications include music recording, instrumentation, electronic cameras, and medical equipment.

Appearance (as manufactured): N/A.

Appearance (as packaged): N/A.

Category II - Item 15

Test Facilities and Equipment

Category II – Item 15: Test Facilities and Equipment

15.A. Equipment, Assemblies and Components

None.

15.B. Test and Production Equipment

Technical Note:
In Item 15.B. 'bare table' means a flat table, or surface, with no fixture of fittings.

15.B.1. Vibration test equipment, usable for the systems specified in 1.A., 19.A.1. or 19.A.2. or the subsystems specified in 2.A. or 20.A., and components therefor, as follows:

a. Vibration test systems employing feedback or closed loop techniques and incorporating a digital controller, capable of vibrating a system at an acceleration equal to or greater than 10 g rms between 20 Hz and 2 kHz while imparting forces equal to or greater than 50 kN, measured 'bare table';
b. Digital controllers, combined with specially designed vibration test "software", with a 'real-time control bandwidth' greater than 5 kHz and designed for use with vibration test systems specified in 15.B.1.a.;

Technical Note:
'Real-time control bandwidth' is defined as the maximum rate at which a controller can execute complete cycles of sampling, processing data and transmitting control signals.

c. Vibration thrusters (shaker units), with or without associated amplifiers, capable of imparting a force equal to or greater than 50 kN, measured 'bare table', and usable in vibration test systems specified in 15.B.1.a.;
d. Test piece support structures and electronic units designed to combine multiple shaker units into a complete shaker system capable of providing an effective combined force equal to or greater than 50 kN, measured 'bare table', and usable in vibration test systems specified in 15.B.1.a.

Technical Note:
Vibration test systems incorporating a digital controller are those systems, the functions of which are, partly or entirely, automatically controlled by stored and digitally coded electrical signals.

Nature and Purpose: Vibration test systems of this type are large and powerful equipment for simulating the flight vibrations and shocks that rockets, unmanned aerial vehicles (UAVs) and their payloads experience during launch, stage separation, and normal flight. Missiles and their subsystems are tested to determine their elastic modes, frequencies, and sensitivities to vibration and shock. This information is used to improve missile design and to qualify systems, subsystems, and components as flight-worthy. Sometimes they are used in quality assurance testing to detect poor connections and loose components.



Figure 132: Vibration testing of a laser altimeter system. (NASA)

A typical vibration test system includes a vibration shaker unit, or thruster, to vibrate test articles attached to it; a power amplifier or other source of power to drive the shaker; a controller to command the power amplifier according to the desired vibration frequency and amplitude test profile; and an air- or liquid-cooling system for the shaker and amplifier.

Method of Operation: Vibration test systems use mechanical thrusters that usually operate on an electromagnetic drive principle like that of an audio loudspeaker, except that they are much larger and drive a massive test item rather than a delicate speaker cone. The digital controllers regulate complex vibration patterns with frequency content of controlled amplitude throughout the 20 Hz to 2,000 Hz range. These patterns are designed to simulate the vibration frequencies and amplitudes expected during the mission, including simulation of vibration bursts or shocks. The output from these controllers must be greatly amplified to drive the thrusters. Hydraulic- and pneumatic-based vibration systems, although capable of the vibration testing of items of MTCR concern, are not generally capable of meeting the above performance specifications.

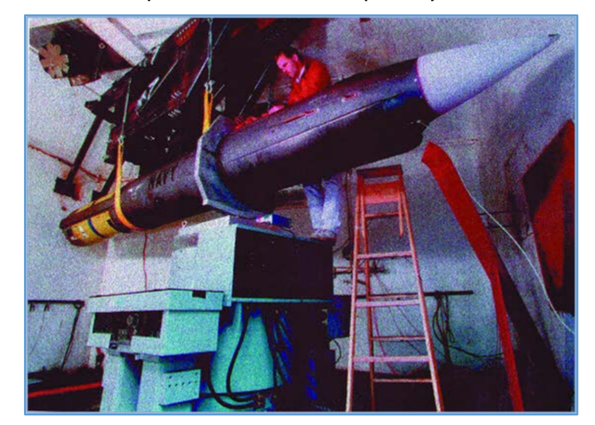


Figure 133: A thruster being prepared to vibration-test a missile. (Unholtz-Dickie)

The armatures of two or more thrusters may be joined together with a test equipment support structure to obtain the required vibration levels. These structures must be both strong and light. Electronic units are needed to control multiple thrusters in a synchronous manner. They accept commands from the digital controller and relay them to multiple amplifiers, each driving one of the thrusters.

Typical Missile-Related Uses: All rockets and UAVs are subjected to vibration and shock during transport and flight. If vibration and shock are properly understood, flight vehicles can be made stronger and lighter because safety margins can be reduced. Use of such equipment also helps avoid costly test flight failures.

Other Uses: Vibration test systems are used to test other military and commercial equipment and products such as aircraft parts. Vibration testing is done on numerous other consumer goods, but MTCR-controlled vibration test systems are much more powerful and expensive than those needed for less demanding applications.

Appearance (as manufactured): MTCR-controlled vibration test systems are large devices that occupy a roughly 3 m x 3 m floor area. Details on the components are given below.

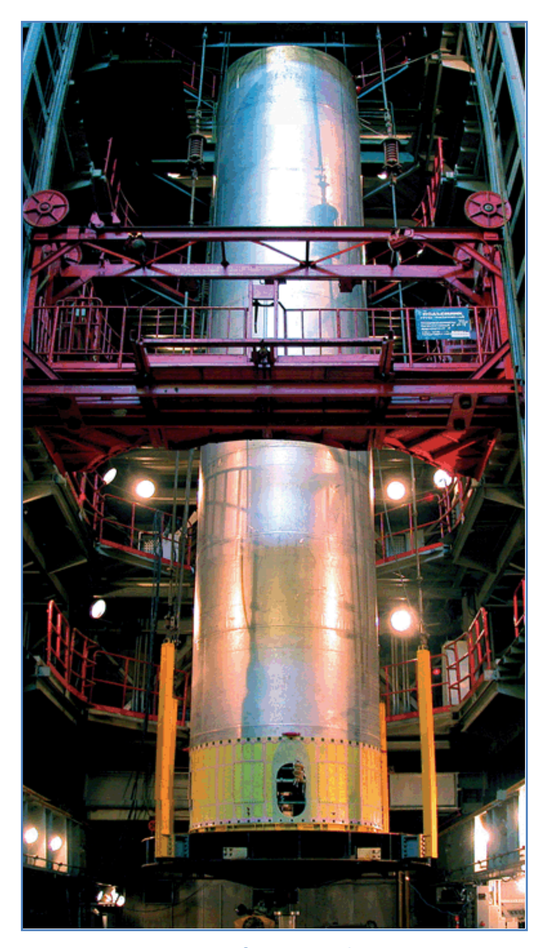


Figure 134: A core first-stage booster in a vibration test rig. (Krunichev Space Center)

Digital controllers and specially designed vibration test software: The digital controller is approximately the same size as the system unit for a personal computer (PC), 0.5 m wide x 0.5 m deep x 0.25 m high. In some cases, the controller is an electronic device small enough to be rack mounted above the power amplifier. In others, a computer is used, complete with monitors and customized interface cards for connection to the power amplifier. Controllers require special purpose vibration control software. Manufacturers of vibration test systems are now offering PC-based software that integrates the functions for test system control, data recording, and data analysis.

Thrusters (shaker units): An MTCR-controlled thruster usually has a very heavy, U-shaped, cast-steel base with thick flanges for securely attaching it to the floor. It measures about 1.3 m on a side and weighs several metric tons. The cylindrical or drum-like steel shaker housing, about 1 m in length and diameter, is hung between the vertical sides of the base. These vertical sides usually have trunnions (pivots) that allow the shaker housing to be rotated to change the thrust direction. Figure 132 shows a satellite laser altimeter undergoing a vibration test. Figure 134 shows a core booster in a vibration test rig.

The part of the thruster that shakes the test item is a round metal armature emerging from one end of the shaker housing. The armature is drilled in a pattern of holes for bolts used to attach the test item. A rubber diaphragm between the armature plate and the thruster housing body is often used to seal the inner workings.

The thruster system may include an accessory slip table (Figure 135), which is often made of magnesium to minimize weight. It supports the weight of the test article on an oil film or air bearing above the slip table base, which is often made of granite. To use the slip table, the thruster itself is pivoted on its trunnions until the axis of motion of its armature is horizontal. The armature is then attached to the side

edge of the slip table in order to vibrate the unit under test in either horizontal axis. Such a slip table assembly has the same size and weight as the thruster assembly itself, and both may be mounted on a common base.



Figure 135: An example of a thruster with slip table. (Kingdom Pty Ltd)

Power amplifier: The power amplifier for an MTCR-controlled electrodynamic vibration test system occupies one or more full racks (each 0.5 m wide x 0.75 m deep x 2 m high) of electronic power control equipment. The electric input power required to drive such a system is about 60 kW to 80 kW. The power draw is so large that it must be hard-wired to the building electrical supply; it cannot use a standard electrical cord and plug.

Cooling: Because the thruster and amplifier give off about one-half of their input electrical power as heat, cooling by forced air or circulating liquid coolant is required. The fan for air-cooling a typical installation measures 1.5 m x 0.5 m x 0.8 m and weighs 200 kg to 250 kg. Liquid cooling circulates cooling water through the test system and into a cooling tower or a radiator equipped with electric fans. Either liquid-cooling system is at least as large as the air-cooling fan. Alternatively, a continuous supply of site water can be simply run through the cooling system and drained away.

- China
- Germany
- Russian Federation
- United States
- France
- Netherlands
- United Kingdom

Global production

Support structures: Test equipment support structures used with such vibration test equipment are custom-made assemblies, which measure as much as 3 m x 3 m x 3 m or more, depending upon the test unit, and weigh as much as 5 tons to 10 tons. Electronic units designed to combine multiple thruster units into a complete thruster system range from an ordinary personal computer (PC) equipped with multiple, special internal interface cards, each controlling a single thruster unit, to one or more racks of custom-built electronic equipment. Recent trends in vibration testing increasingly use PC-based systems because they provide flexibility at low cost. Because specialized vibration system control interface cards are installed within the PCs, it may not be evident from external examination that the PCs are MTCR-controlled.

Appearance (as packaged): With the exception of the system controller, which is typically the same size as a personal computer (PC) and can be packaged for shipping in typical PC packaging, the components of

a vibration test system of MTCR concern are so large and heavy that they must be packaged in custom-built wooden crates of extremely robust construction.

15.B.2: 'Aerodynamic test facilities' for speeds of Mach 0.9 or more, usable for the systems specified in 1.A. or 19.A. or the subsystems specified in 2.A. or 20.A.

Note:

Item 15.B.2. does not control wind tunnels for speeds of Mach 3 or less with dimension of the 'test cross section size' equal to or less than 250 mm.

Technical Notes:

1. 'Aerodynamic test facilities' includes wind tunnels and shock tunnels for the study of airflow over objects.

2. 'Test cross section size' means the diameter of the circle, or the side of the square, or the longest side of the rectangle, or the major axis of the ellipse at the largest 'test cross section' location. 'Test cross section' is the section perpendicular to the flow direction.

Nature and Purpose: Wind tunnels are large enclosures in which air is circulated or blown through a test section containing a replica of the rocket or UAV, sometimes full size but often a scale model. They are used to measure the aerodynamic performance of the airframe design during a simulated flight through the atmosphere. Instrumentation in the test section gathers data on vehicle lift and drag, stability and control, engine inlet and exhaust configuration, thermal effects, and infrared signature. Wind tunnels are of either the continuous-flow type or the blow-down (e.g., shock tube) type and measure aerodynamic parameters for long or short duration, respectively. Some continuous-flow tunnels circulate the same air around, while others draw fresh air in at one end and return it to the atmosphere at the other end.



Figure 136: A hypersonic wind tunnel capable of equaling Mach 5 to test flight conditions for launch vehicles. (Mitsubishi Heavy Industries, Ltd)

Method of Operation: A continuous-flow wind tunnel uses one or more large fans to achieve the desired speed of air in the test section. The test section might be called the throat because the rest of the tunnel has a larger cross section with slower air speeds, including through the fan. Past the test section, the air slows through a diffuser and then circulates back through the fan to create a continuous flow of air past the test object.

Alternatively, some wind tunnels simply draw air in from the atmosphere at one end through an entrance cone, essentially a large rectangular funnel as seen in Figure 137. In such a “once through” wind tunnel,



Figure 137: A large wind tunnel facility originally built for circulation through the loop of buildings in background. Entrance cone in foreground was added to also permit once-through operation using the same fans. (NASA)

the air simply exits to the atmosphere after slowing down past the test section. While the latter type of tunnel can have a straight and simplified design for cost effectiveness, more fan power is required to continuously bring air up to speed from a standstill. Conversely, an advantage of circulating wind tunnels is that the enclosed mass of air keeps moving, reducing power requirements.

In order to avoid the need for an extremely powerful fan to achieve the highest speeds, a blow-down wind tunnel operates transiently in the once-through mode while avoiding fans altogether. Air or another gas is stored in a large reservoir at high pressure, then released through a control valve into the tunnel and onward through the test section and out.

Typical Missile-Related Uses: Wind tunnels capable of exceeding Mach 0.9 are used to test rockets, supersonic UAVs, and re-entry vehicles. For high-speed flight, generally above Mach 3, heat transfer tests may be conducted. High-enthalpy, continuous-flow tunnels, or alternatively shock tubes, are needed to produce wind speeds beyond Mach 5 for testing long-range ballistic missiles or hypersonic vehicles (Figure 136).

Other Uses: Wind tunnels are used in designing aircraft for all speed ranges including supersonic.

Appearance (as manufactured): A wind tunnel for testing small-scale models might fit entirely within one room in a building. Its test section and other tunnel sections may be either circular or rectangular in cross section. Wind tunnels for testing full size rocket or UAV systems are more typically rectangular. The latter are large facilities with several buildings housing the test section, compressors (fans), data acquisition systems, and power supplies (Figure 6). Historically, the largest wind tunnels for testing aircraft have not achieved speeds approaching Mach 0.9.

A continuous-flow wind tunnel suitable for testing full size missiles is usually 50 m to 100 m in length and 25 m to 50 m in width, with diffusers (gradually expanding cones) 10 m to 15 m in diameter. The larger-size wind

- Canada
- France
- Japan
- Netherlands
- Switzerland
- United States
- China
- Germany
- India
- Russian Federation
- United Kingdom

Global production





Figure 138: Test objects in test section of a hypersonic wind tunnel. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))

tunnel is generally laid out in a horizontal oval 10 to 20 times the length of the test section length and 5 to 10 times its width. The tubular sections of the tunnel are generally made of steel plates welded together to form the circuit, which is supported from the outside by steel structures. Some wind tunnels use adjustable nozzle sections to vary the characteristics of the airflow.

Test sections typically have access doors so that test objects can be moved into and out of the wind tunnel and mounted on the test support. Typically, the test support structure incorporates force measurement instruments to determine the aerodynamic lift and drag forces, and the rotational moments (torques) being experienced by the aerodynamic model under test. The test section may have windows for observing supersonic air flow around the missile with special Schlieren photographic recording devices (or other non-intrusive flow visualization devices). The test section of a large tunnel usually has an associated operations building that houses the controls and data collection instrumentation, and may handle the insertion, positioning, or removal of test objects. Testing of full size missiles in continuous-flow wind tunnels produces the most accurate results but requires high power (on the order of 200,000 hp) to move the large volumes of air at flight speeds.

The blow-down tunnel stores air or other gases under high pressure in large tanks or cylinders. An air duct sealed by a large valve or diaphragm connects the tanks to the tunnel entrance cone and test section. The tunnel walls are generally made of relatively thick steel and are sometimes coated with insulation because of the high temperatures generated by very high wind speeds. A large compressor is used to pump air under pressure into the tanks before each test.

Aerodynamic test facilities for the highest speeds are typically of the blow-down type. They are likely to be referred to as shock tubes instead of being called wind tunnels, and they are likely to be sized only for small scale models. In order to withstand extremes of pressure and temperature, they may consist of round metal pipes, and test sections are not likely to have doors. Sections of pipe or tube are joined by flanges so that the test section may be readily removed to place test models inside the tube.

Appearance (as packaged): The largest wind tunnels are custom-designed and constructed on site. Even relatively small wind tunnels that fit in one room, and which might be serially manufactured, are typically not fully assembled prior to shipping. Individual components like the compressor motor, fan blades, corner turning vanes (for circulating tunnels), complete test section or test section walls, viewing windows, and control and instrumentation panels are crated or mounted on pallets for shipping. Tunnel walls are generally shipped as structural components to be assembled together at the facility location.

15.B.3. Test benches/stands, usable for the systems specified in 1.A., 19.A.1. or 19.A.2. or the subsystems specified in 2.A. or 20.A., which have the capacity to handle solid or liquid propellant rockets, motors or engines having a thrust greater than 68 kN, or which are capable of simultaneously measuring the three axial thrust components.

- China
- France
- Germany
- Netherlands
- Russian Federation
- United Kingdom
- United States

Global production

Nature and Purpose: Considering the thrust threshold of 68 kN (roughly 15,000 pounds), test benches and test stands tend to include large rigid structures, for testing rocket systems, solid, hybrid or gel propellant rocket motors, and liquid rocket engines. They securely hold test items being operated at full thrust while collecting performance data on critical parameters. These data support design development and confirm design integrity and performance, including reliability and operating lifetime. Liquid rocket engines are sometimes tested in test stands to verify performance before delivery.

Method of Operation: The test item is mounted on the test bench or test stand. Sensors are positioned and checked. Personnel are cleared from the test area, and data are collected with sensors and stored remotely while the rocket is operated.

Large solid rocket motors have traditionally been tested horizontally though some may be tested vertically. Large liquid rocket engines are usually tested vertically or horizontally while propellants are supplied from facility tanks. Sometimes complete liquid stages are tested (i.e. including flight tanks) vertically so the liquids reach the lower ends of the tanks and hence the engine feed ducts. Liquid rocket stages are placed on the test stand before propellant loading, so they are lightweight and relatively easy to raise into a vertical position. Sensors measure pressures, propellant flows, forces, event timing, vibrations, displacements, and temperatures. Rocket motors run to exhaustion and burnout; by contrast, liquid rocket engines and hybrid or gel propellant rocket motors can be throttled or shut down. Post-test inspections are conducted, and data are analyzed.

Typical Missile-Related Uses: Test benches and stands are essential equipment in the development phase of a missile program. Liquid rocket engine test stands are also used for full-scale testing of engine components such as injectors, combustion devices, and turbopumps.

Other Uses: Similar, though often smaller, horizontal test benches and stands are used to test jet engines, including for use in UAV systems, including cruise missiles. While jet engines are tested in a horizontal position, their test stands are often vertical structures that elevate the engines above the ground, for personnel safety and to obtain air that is free of loose objects and debris that may be on the ground within reach of the air inlet.



Figure 139: The load measurement system on the test stand of a solid rocket motor. (ATK)

Appearance (as manufactured): A horizontal solid propellant rocket motor test stand (Figure 139) generally consists of a dolly, thrust cup, load cell, thrust block, and instrumentation. The solid rocket motor is first secured horizontally on a movable dolly and locked down. Larger motors are often connected to a frame, which is then inserted into the thrust-cup; smaller motors are often inserted directly into the thrust-cup. The thrust-cup is mated to a load cell assembly which measures the three thrust components, one axial and two sideways, the latter to verify that off-axis forces are small. The load cell structure might also be designed to measure torques (rotational forces). The load-cell assembly is mounted on a large concrete block or metal frame called the thrust block, which absorbs the forward force variations as the motor is being fired. Instrumentation connected to the load cell sends data to a blockhouse containing recording equipment. The entire assembly is usually outdoors but may be either partially or totally enclosed in a concrete building or a trench.

Liquid propellant rocket engines use vertical test stands, large gantry-type structures made of steel beams and girders (Figure 140). For horizontal testing, liquid rocket test stands are close to the ground, typically consisting of a concrete pad supporting a metal structure to mount the engine on. The liquid rocket engine is attached to load cells, which measure the thrust components as noted above; these data are sent to a block house for recording. Run tanks carrying the propellants, the flame bucket, and usually a concrete apron that directs the exhaust away from the test stand are also parts of the installation.



Figure 141: A vertical test stand designed for testing liquid propulsion rocket engines. (Interorbital Systems)



Figure 140: A solid propellant rocket motor on a test stand. (Avio SpA)

Appearance (as packaged): Rocket test benches and stands are custom designed and typically constructed on site, so they are seldom shipped as assembled structures. A review of the design drawings and fabrication or assembly instructions can identify the intended use of the construction materials and components.

15.B.4. Environmental chambers as follows, usable for the systems specified in 1.A. or 19.A. or the subsystems specified in 2.A. or 20.A.:

a. Environmental chambers having all the following characteristics:

1. Capable of simulating any of the following flight conditions:

a. Altitude equal to or greater than 15 km; or

b. Temperature range from below -50 °C to above 125 °C; and

2. Incorporating, or designed or modified to incorporate, a shaker unit or other vibration test equipment to produce vibration environments equal to or greater than 10 g rms, measured 'bare table', between 20 Hz and 2 kHz while imparting forces equal to or greater than 5 kN;

Technical Notes:

1. Item 15.B.4.a.2. describes systems that are capable of generating a vibration environment with a single wave (e.g. a sine wave) and systems capable of generating a broad band random vibration (i.e. power spectrum).

2. In Item 15.B.4.a.2., designed or modified means the environmental chamber provides appropriate interfaces (e.g. sealing devices) to incorporate a shaker unit or other vibration test equipment as specified in this Item.

b. Environmental chambers capable of simulating all of the following flight conditions:

1. Acoustic environments at an overall sound pressure level of 140 dB or greater (referenced to 2×10^{-5} N/m^2) or with a total rated acoustic power output of 4 kW or greater; and

2. Any of the following:

a. Altitude equal to or greater than 15 km; or

b. Temperature range from below -50 °C to above 125 °C.

Nature and Purpose: Environmental testing in ground facilities exposes components, subsystems, and entire vehicles to the low pressures, high and low temperatures, vibrations, and acoustics of powered flight in order to measure the responses. The data generated are used to confirm or correct designs and thereby ensure flight worthiness.

Method of Operation: High altitude is simulated by sealing test objects into rugged pressure chambers that are then evacuated with vacuum pumps. Flight temperatures are simulated inside thermally insulated chambers equipped with heaters and refrigeration equipment. MTCR-controlled temperature chambers must also be equipped to replicate specific vibration or acoustic environments. Vibration equipment are motor-driven tables capable of providing amplitude-frequency spectra to the levels stated above and replicating the range of vibrations experienced by a component, subsystem, or system during powered

flight. Acoustic chambers use a combination of electrostatically or electromagnetically driven horns, like loudspeakers, to provide a spectrum of sound pressures like those generated by rocket motor exhaust and very high-speed aerodynamic flight.

Typical Missile-Related Uses: Altitude tests are used to investigate engine performance, heat transfer, altitude ignition, nozzle development, and propellant dynamics phenomena. Simultaneous temperature-vibration and temperature-acoustic tests are used to subject missile hardware to high-fidelity flight environments to develop technology and qualify missiles for flight. Such testing is not required for basic missile programs, but is necessary for advanced development. This equipment can also decrease the cost of a flight test program, but some of this equipment, particularly the large environmental chambers, can be quite expensive.



Figure 142: A full scale solid rocket engine being tested at simulated high altitude. (AEDC)

Other Uses: High-altitude and simultaneous temperature-vibration and temperature-acoustic testing is routinely done on satellites and aircraft components.

Appearance (as manufactured): Environmental pressure chambers are rugged, usually metal, airtight, cylindrical chambers with bulged or hemispherical ends to withstand the external pressure of one atmosphere (plus safety margin). They often have thick glass or acrylic viewing ports. An access panel or door at one end is used to insert and remove test items. They are often linked to large vacuum pumps that evacuate the chamber. Their size is a function of the items to be tested; thus, they can range from less than a meter to tens of meters on a side. They are usually supported by numerous buildings housing pumps, power, data collection, and operations. Figure 142shows an interior view of a solid rocket motor being tested at simulated altitude.

- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Russian Federation
- United Kingdom
- United States

Global production



Temperature chambers are thermally insulated chambers or rooms with heating and cooling equipment. MTCR-controlled temperature chambers have provisions for vibration or acoustic testing at various temperatures encountered in flight.

Temperature chambers for vibration testing contain a powerful device to shake test items.



Figure 143: A vibration and environmental test apparatus configuration. (TUV Rheinland)

This device, known as a thruster or shaker, usually has a round, flat, steel table, which may have predrilled/tapped mounting locations for attaching test articles. Table motion is often driven by a cylindrical, variable-speed linear electric motor. Depending on the size of the items tested, these tables range from tens to thousands of kilograms in weight (Figure 143 & Figure 144). Environmental chambers controlled under this item can simulate flight conditions of 10 g rms or more from 20 Hz to 2,000 Hz, impart forces of 5 kN or greater, and have operating temperatures of below –50 °C to above +125 °C. Figure 143 shows a combined environmental/vibration test apparatus.

Temperature chambers for acoustic testing are large rooms with acoustic horns mounted in the walls. The horns themselves are monotonic (operate at one frequency) and range in length from several centimeters for high-frequency horns to 1 m for low-frequency horns, with corresponding exit area, or mouth, sizes. Acoustic testing usually requires that the chamber be lined with very coarsely corrugated (often conic-shaped), soft, porous, sound-absorbing material.w

Appearance (as packaged): Environmental chambers vary in size, but they are usually very large and constructed onsite. Large MTCR-controlled temperature chambers may be shipped as prefabricated panels of construction materials. The assembly instructions or construction plans can help identify intended use. Smaller temperature chambers are shipped much like a common refrigerator. Dynamic test tables in a partially assembled state are shipped in simple wooden crates, usually with some internal contouring and cushioning for the parts. The shipping containers of these rugged pieces of equipment are not likely to have any special handling markings. Acoustic horns are shipped in metal canisters or wooden crates. Because the driver diaphragms in these horns are sensitive components, shipping containers may have special handling markings.


Figure 144: A controlled environmental chamber with vibration capability. (RMS Dynamic Test Systems)

15.B.5. Accelerators capable of delivering electromagnetic radiation produced by bremsstrahlung from accelerated electrons of 2 MeV or greater, and equipment containing those accelerators, usable for the systems specified in 1.A., 19.A.1. or 19.A.2. or the subsystems specified in 2.A. or 20.A.

Note:
15.B.5. does not control equipment specially designed for medical purposes.

- China
- Germany
- India
- Japan
- Russian Federation
- United Kingdom
- United States

Global production

Nature and Purpose: MTCR-controlled accelerators are of three basic types: linear radio frequency (RF) accelerators (linac), flash X-ray machines, and mechanically charged, high-voltage electrostatic accelerators (Van de Graaff type). Their primary use is to create X-rays capable of penetrating missile parts (such as solid propellant rocket motors) so that X-ray photographs can be made of their interiors. Other uses for energetic X-rays include simulating nuclear weapon effects and stop-action X-ray photography of very high- speed events like explosions and impacts.

Method of Operation: The accelerators of most interest are the linac type. They accelerate a beam or cluster of electrons to speeds approaching the speed of light by passing them through cavities charged with an electric potential (voltage) supplied by an RF generator. Because the effect of these cavities is additive, total electron energies of millions of electron volts (MeV) can be obtained from relatively small devices. This energetic beam of electrons exits the linac and strikes a target (usually a dense metal such as tungsten). The electrons give off X-ray radiation as they are decelerated inside the target; this phenomenon is called “bremsstrahlung,” German for braking radiation. The X-rays pass through the object and are recorded on film or, increasingly, in electronic sensors that immediately display the picture on a computer screen. A Van de Graaff accelerator normally creates a large electrostatic potential by mechanically driving a vulcanized rubber belt or insulating string of polished metallic beads on an insulating surface. The targets used to stop the electrons in the electrostatic generators are metal foil like that used in linear accelerators. Most flash X-ray machines operate by charging a very large bank of capacitors to high voltage and then suddenly discharging them. Like the linac, the resulting electron current strikes a heavy metal target and creates X-rays.

Typical Missile-Related Uses: One of the most important uses of linacs is to produce X-rays for non-destructive testing of solid rocket motors. They are used to find cracks and voids in the propellant grain, cracks and incomplete welds in the case, or incomplete bonds to the insulation or interior lining. Such X-ray equipment can be used to inspect most missile components such as structural members, welds, nozzles, and turbopump parts. If any of these quality issues are present and are not detected they can result in catastrophic failure of the motor stage, thus the critical need for this equipment. Linacs are also

used to investigate nuclear radiation effects of missile electronics and to test equipment and parts for radiation hardness. These are also the primary uses of large flash X-ray machines. Van de Graaff accelerators are not usually used for these purposes because of their size and low beam current (and thus low X-ray) output.

Other Uses: Industrial microwave, accelerator- based, high-energy X-ray machines have been routinely used for a wide variety of industrial applications for more than 30 years. These applications include defect-detection of large castings and welded assemblies used in automotive, shipbuilding, aerospace, and power production component manufacturing. These machines also are used in large security systems for detection of contraband or explosives in container shipments. Similar technology is employed in the production of machines used to treat cancer.

Appearance (as manufactured): The most commonly used 2+ MeV accelerator is the linac, as shown in Figure 145, because of its small size and ruggedness. These X-ray machines consist of five major parts: the accelerator, the X-ray head, the RF amplifiers or modulators, a control console, and a water pump cabinet. The box-like structure of Figure 145 contains the accelerator and the X-ray head.

The source of the X-rays is the X-ray head. It is connected to the RF modulator by means of a waveguide, which is a rectangular rigid or semi-rigid conduit or cable. The accelerator portion of the X-ray head is a tube or pipe with semicircular disks on alternating sides along its length. This assembly may be in the center of a larger diameter electromagnet. The modulator or RF amplifier, which supplies RF energy to the acceleration tube, is often in a separate cabinet. This energy is normally coupled through a rectangular waveguide or, less frequently, a coaxial cable. The modulator operates at a frequency corresponding to the accelerating structure, normally in the 1 GHz to 3 GHz range. The other supporting components are the control system and the water-cooling system. These systems control and cool the accelerator to keep it within a narrow range of operating temperatures. Typical dimensions for the X-ray head, modulator cabinet, and control console are shown in Table 1.



Figure 145: Typical linac X-ray system. (Varian Associates)

X-rays produced by MTCR-controlled accelerators are energetic enough to require lead shielding several centimeters thick. These accelerators are often shipped without shielding since the shielding can be readily manufactured and installed by the recipient. Often an unshielded system is placed inside a shielded building.

The other type of accelerator for use in high-energy X-ray generation is a mechanically driven Van de Graaff type generator. These systems are much larger than linear accelerators and more difficult to position, and thus are not normally used for radiography. They consist of a high-voltage power supply capable of generating electrostatic potentials of 2 MeV or more, an acceleration tube made of highly polished nickel, and a control console. The power supply and the acceleration tube are usually integral parts. They are contained within a high-pressure tank made of thick-walled steel, which when operational,

contains a high dielectric gas such as sulfur hexafluoride or pure nitrogen at a pressure of several atmospheres. Unlike the linear accelerators, which are small enough to be rotated around the piece being X-rayed, the very large electrostatic accelerators remain stationary, and the test piece is moved as needed to achieve the desired relative positioning. Typical dimensions of a Van de Graaff system are given in Table 2.

Table 1: Typical Linac Dimensions

	X-ray Head	Modulator Cabinet	Control Console
Height	0.5 m	1.0 m	0.2 m
Width	0.5 m	0.5 m	0.3 m
Depth	1.0 m	1.0 m	0.3 m
Weight	200 kg	300 kg	3 kg

Table 2: Typical Dimensions for a Van de Graff system

	Pressure Vessel	Control Console
Length	2.5 m	0.2 m
Diameter	1.0 m	
Width		0.2 m
Weight	1,200 kg	2 kg

Flash X-ray equipment varies in size from a desktop unit to huge systems that require special buildings. A typical unit used for inspection of solid rocket motor propellant grains is shown in Figure 146.



Figure 146: A 2.3MeV flash X-ray unit used for inspecting solid rocket motors. (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))

Appearance (as packaged): Linear accelerators are packaged for shipment in crates or boxes. They may appear as three separate cabinets. The X-ray head and modulator normally come from the same vendor. The cooling system and the control system can be purchased separately.

The packaging uses foam, Styrofoam, or other shock-attenuating fill to protect the modulator from excessive vibration and shock. The equipment may be labeled with X-ray caution labels, RF field signs, and possibly labels indicating high-voltage. The system may be heavier than lower-energy systems because of the amount of lead shielding, if shipped with shielding installed, required to shield personnel from penetrating X-rays.

The electrostatic accelerators are much larger. The high-voltage supply and the acceleration tube are shipped together inside the pressure vessel. Because of its weight, the pressure vessel is most likely shipped in a crate made for fork-lift handling. The unit is not likely to be shipped in operational condition and usually has additional packing material inside the pressure vessel to support the high-voltage supply and acceleration column.

15.B.6. 'Aerothermodynamic test facilities', usable for the systems specified in 1.A. or 19.A. or the subsystems specified in 2.A. or 20.A, having any of the following characteristics:
a. an electrical power supply equal to or greater than 5 MW; or
b. a gas supply total pressure equal to or greater than 3 MPa.

Technical Note:
'Aerothermodynamic test facilities' include plasma arc jet facilities and plasma wind tunnels for the study of thermal and mechanical effects of airflow on objects.

- Belgium
- China
- France
- Germany
- Israel
- Italy
- Japan
- Russian Federation
- United States

Global production



Nature and Purpose: Aerothermodynamic test facilities simulate the harsh flow environment that a missile encounters while flying at very high speeds such as those associated with ballistic re-entry. Aerothermodynamic test facilities are also used in the development of thermal protection systems for ballistic missiles.

Plasma arc jet facilities provide high speed temperature flows capable of reproducing temperatures and heat-fluxes associated with reentry aero-heating local to the test article. A plasma wind tunnel (plasma arc tunnel) incorporates a plasma to simulate the aerodynamic heating and flow near the surface of the missile flying at very high speed.

Method of Operation: An arc jet (Figure 147) is a device in which gases are heated and expanded to very high temperatures and supersonic/hypersonic speeds by a continuous electrical arc between two sets of electrodes. A high voltage source produces an electrical arc which superheats the test gas to the point of ionization. The gases (typically air) pass through a nozzle aimed at a test sample in vacuum, and flow over it, producing a reasonable approximation of the surface temperature and pressure and the gas enthalpy found in a high velocity, supersonic flow of the kind experienced by a vehicle during atmospheric reentry.

Plasma wind tunnels use a high-current electric arc to heat the test gas to very high temperature. The plasma conditions in a plasma wind tunnel are determined by the plasma source used, the operating parameters and the position of the test article in the plasma beam. A plasma wind tunnel consists of an arc chamber, a nozzle, a test chamber, and a vacuum system for maintaining the test chamber at low pressure. Cold test gas flows through the arc chamber and nozzle. An electric arc is established through the gas between an insulated electrode in the arc chamber and some surface of the arc chamber. The electric arc raises the temperature of the test gas to ionization level yielding a plasma, which is a mixture of free electrons, positively charged ions, and neutral atoms. Argon is typically used as the test gas instead of air due to the higher degree of ionization achievable for a given power input.



Figure 147: Interaction Heating Facility (60 MW) arc jet. (National Aeronautics and Space Administration (NASA))

To reproduce the flow conditions near the test item's surface present during actual high speed flight as accurately as possible in the plasma wind tunnel, the characteristics of the plasma beam and the changes in material to be examined must be determined as exactly as possible.

Typical Missile-Related Uses: Aerothermodynamic test facilities with an electrical power supply equal to or greater than 5 MW or a gas supply total pressure equal to or greater than 3 MPa are used to test missiles at reentry environmental conditions.

Other Uses: Aerothermodynamic test facilities are also used to test thermal protection systems on space craft at reentry environmental conditions and at environmental conditions associated with planetary explorations. Some high temperature plasma systems have industrial applications in the high-temperature gasification of biomass and non-hazardous waste, the destruction of hazardous waste (such as fly ash and asbestos), the reduction and immobilization of low-level radioactive waste and in the steel industry.

Appearance (as manufactured): Arc jet and plasma wind tunnel facilities can vary in size from small-scale models that fit in a room of a building (Figure 148) to facilities that encompass an entire high-bay to large complexes with several buildings that house the various components of the arc jet system (Figure 18).

Appearance (as packaged): The arc jet facilities and plasma wind tunnels are typically custom-designed and constructed on site. The components of arc jet and plasma wind tunnel facilities such as the test sections, control and instrumentation panels are crated and mounted on heavy pallets for shipping.

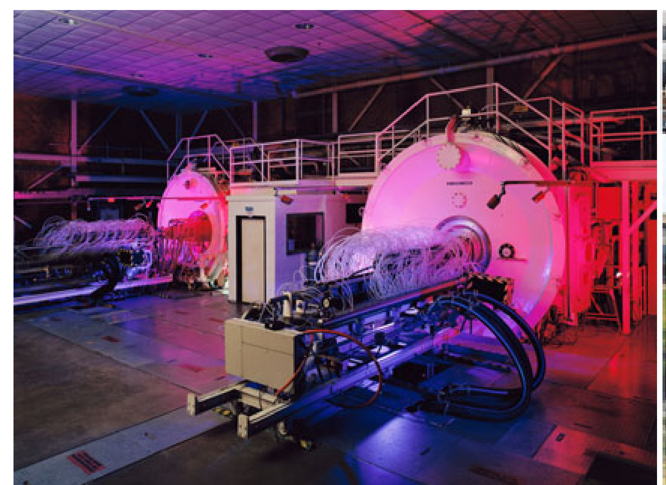


Figure 148: Image of the interior of the Johnson Space Center (JSC) Atmospheric Reentry Materials and Structures Evaluation Facility (Arc-Jet) (NASA)



Figure 149: Aerial Overview of the Arc Jet Complex at NASA Ames Research Center (NASA)

15.C. Materials

None.

15.D. Software

15.D.1. "Software" specially designed or modified for the "use" of equipment specified in 15.B. usable for testing systems specified in 1.A., 19.A.1. or 19.A.2. or subsystems specified in 2.A. or 20.A.

Nature and Purpose: Software used in rocket and UAV system test facilities is sometimes specifically designed to operate specialized test equipment and to record the results of the test for later analysis. In some instances however, modern general-purpose software can be configured by the end-user to meet the needs of such test facilities. One general function of software is to automatically operate specialized test equipment, while a second function is to collect and store test data. The latter function, data acquisition, is more likely to be done using general purpose software that is not controlled in Item 15.D.1. A third function is to analyze test results, which might be done using specialized software, or by general purpose software that is specially configured.

For example, software used to operate vibration test systems provides appropriate signals to digital controllers that simulate the vibrations associated with ballistic missile powered flight. This signal can be varied over a range of frequencies and amplitudes. The facility computer system records accelerometer signals to determine the vibratory response of the test article, such as an avionics board, a solid-state gyroscope, or a propulsion component. Another example of a software task is to collect wind tunnel data during instrumented airframe tests. Computerized systems can record wind speed and the resulting lift, drag, stability, thermal effects and infrared signature data generated by the test article. Solid propellant rocket motor and liquid propellant rocket engine test software collect information from instrumented motor and engine components while the motor/engine is tested. Test results include startup transient and operating pressures, motor case deformations, thermal data and motor/engine performance data among other readings. All this data is analyzed to evaluate rocket subsystem performance and design suitability.

Method of Operation: A typical vibration test system includes a shaker unit to vibrate test articles attached to it; an electrical power amplifier or another source of power (e.g. hydraulic) to drive the shaker; a controller to command the power amplifier according to the desired vibration frequency and amplitude test profile; and an air- or liquid-cooling system for the shaker and amplifier. The test article is securely mounted onto the vibration table fixture, while the test article has its own mounted sensors and other instrumentation pickoffs, typically small self-exciting piezoelectric accelerometers. Other signal cables are attached to record any internal electrical responses or signal changes that may occur during the test. The operator inputs vibration frequency and the amplitude information to the computer controller which then translates this input into signals sent to the power amplifier which controls the shaker table.

Software used to support wind tunnel and solid propellant rocket motor or liquid propellant rocket engine test firings may have a programmed sequence of wind tunnel speeds and times, or a programmed sequence of valve openings and closings in the case of liquid rocket testing. Simultaneously during testing,

other software collects data from instrumentation systems and sensors mounted on the test article. While the data acquisition function might be done by a separate computer, modern general purpose software makes it possible to run tests and collect data with one computer. The data-acquisition side of the software may have built-in analytic capabilities to assist the missile engineer evaluate the results of the test.

Typical Missile-Related Uses: This type of software controls test equipment that simulates the environment a rocket or UAV system will experience in flight without having to consume a missile for test. The application of sound ground testing procedures on flight systems reduces the time and cost of developing these subsystems.

Other Uses: This type of software is available to other industries. Vibration test stations and wind tunnels are used to test other military and civilian products, such as aircraft. The same software, perhaps with minor modifications, is used to control the operation of these pieces of test equipment and to monitor the results from the test articles. General purpose software for test instrumentation (e.g. LabVIEW™) is used for a wide variety of purposes and is not controlled in Item 15.D.1.

Appearance (as manufactured): Typically this software takes the form of a computer program that historically would have been stored on printed, magnetic, optical or other media, but which might also be sold and transferred directly over the internet. Any common media including magnetic tape, floppy disks, removable hard disks, USB flash drive, compact discs and documents can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, USB flash drive, compact discs and documents containing this software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. The software of interest, including the documentation, is capable of being transmitted electronically over a computer network.

15.E. Technology

15.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or "software" specified in 15.B. or 15.D.

Nature and Purpose: The technology to develop test facilities and equipment, which are in turn used to develop and produce rockets or UAVs, involves a thorough understanding of both the flight systems to be tested and the expected response to testing. Experience is also required to design, build, and operate test equipment that is precise enough to accurately simulate the flight environment while recording measurements. In the absence of technology transfer, a country might develop specialized test software or configure general purpose software over time as it gains information based on experiments. Engineering drawings (sometimes referred to as blueprints) detailing how to manufacture or operate missile-related test equipment obviously would be critical pieces of technology. Transferring know-how for generating or configuring testing and analysis software would similarly constitute a transfer of MTCR-controlled technology.

Method of Operation: Technical assistance is available in many forms. Technical assistance may consist of instruction provided by a person experienced in one or more controlled subjects such as large vibration test equipment or liquid propellant rocket engine testing, who acts as a trainer in a classroom on or near the production site. A country may receive technical assistance from one or more consulting services that specialize in a particular production skill. A country may receive procurement assistance either in the form of the provision of technical equipment, machines, or materials, or in the form of assistance in determining the item needed for the program. Finally, a country may receive technical assistance by sending students to other countries possessing the technology to attend training and practice the skills necessary to build and operate the required systems.

Typical Missile-Related Uses: Technical assistance required to build and operate rocket or UAV test equipment may be used only for those purposes (e.g. in the case of test stands) or may be useful in a variety of civil and military applications. Space launch vehicles and sounding rockets used in weather research are, with minor adjustments, ballistic missiles, and the technology used in ballistic missiles and in space launch vehicles or sounding rockets is essentially the same.

Other Uses: Civil and military aircraft may use scaled down versions of this technology. Likewise, this technology may be used to test sensitive subsystems and components for ground vehicles.

Appearance (as manufactured): N/A.

Appearance (as packaged): N/A.

Category II - Item 16

Modelling-Simulation and Design Integration

Category II – Item 16: Modelling-Simulation and Design Integration

16.A. Equipment, Assemblies and Components

16.A.1. Specially designed hybrid (combined analogue/digital) computers for modelling, simulation, or design integration of systems specified in 1.A. or in the subsystems specified in 2.A.

Note:
This control only applies when the equipment is supplied with "software" specified in 16.D.1.

- Australia
- Canada
- France
- India
- Italy
- Norway
- South Africa
- Sweden
- United Kingdom
- Brazil
- China
- Germany
- Israel
- Japan
- Russian Federation
- Republic of Korea
- Ukraine
- United States

Global production



Nature and Purpose: Modelling, simulation, and design integration software tools provide affordable means for planning and optimizing ultimately high-cost space and military missions and operations. In permitting the designer to build and fly rocket systems and unmanned aerial vehicles (UAVs) using computers, numerous design changes and flight environments can be investigated and tested using software tools, thereby reducing the expense of building, testing, and iteratively redesigning flight hardware. Mathematical modelling capability dramatically decreases the cost and time required to develop a rocket or UAV. Various computer-generated codes have a critical role in designing a missile with desired performance capability, especially for longer range missiles. Using a full library of software models to validate performance in the design stage leads to missiles with the most appropriate, mission related trade-offs, including range and payload capabilities.

Hybrid computers combine analog and digital components to exploit the advantages of each. In addition to historical usefulness in design modelling, there have been applications for real-time data processing. They are useful in situations in which data rates are extremely high and the signal-to-noise ratio is low, such as focal plane arrays in advanced sensors. These conditions may be stressful to purely digital computers because such computers cannot always keep up with the data stream, and the low signal strength sometimes does not create the clear “1” or “0” required by a digital device. Thus, analog circuitry has sometimes been used to collect and process the output of the sensor before digitizing the data.

Method of Operation: Most missile design software models represent the physics of missile operation to test the structural characteristics of missiles and components (Figure 150 and Figure 151). Modern aerodynamic models may offer a highly accurate treatment of flows internal and external to the missile and can be tailored to the specific missile geometry under evaluation.

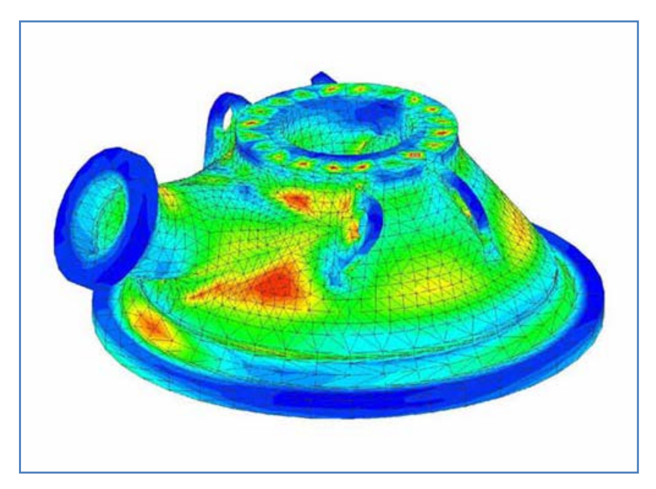


Figure 150: Modelling and simulation software has been used to analyze the structure of rocket engines and components, satellite thrusters, propellant tanks and antenna. (EADS)

Thermodynamic models predict both the frictional heating and chemical reactions involved in missile propulsion and thermal protection, and the resulting flow of heat into critical missile components. Applications of finite element models in designing missile structures are now common, as are applications of models combining guidance hardware and missile controls to test performance. Once designed, subsystem hardware is frequently tested by means of hardware-in-the-loop simulators. Hardware-in-the-loop refers to testing activities that are partly simulated and partly real, such as bench testing the steering system for a missile using real fins and actuators, while a computer simulates the resulting flight path with a mathematical model for the entire missile in flight. For a “closed-loop” test, the computer would use the calculated flight path to produce simulated navigation sensor data to feed into the real steering system being tested. The complexity of such testing can range widely, i.e. the actual hardware under test might be one mechanical linkage or it might be a complete guidance and control subsystem.

Typical Missile-Related Uses: Missile design software may be applied in a variety of ways during the early phases of the design process. Modelling and simulations can be used to define and test the parameters and functions of sensors and other communications equipment, as well as weapons payload; and to create and define multiple configurations, thrust capabilities, aerodynamic flight loads, structural requirements, thermal insulation requirements, and the guidance or control requirements of candidate design concepts, or models. Subsystem hardware designs based on these models are performance tested, often with simulation software in-the-loop, to validate their capabilities and to refine the models to make them more design specific. The computer then combines these design-specific models in order to represent an integrated rocket or UAV system in flight and to confirm its design capabilities before actual flight testing. This modelling approach eliminates much of the need for expensive iterative flight testing.

Other Uses: Many of the more fundamental software models used in missile system design are commonly used commercially. Structural modelling techniques are used in designing cars, trucks, passenger airplanes, buildings and other infrastructure. Thermodynamic codes are used in the design of satellites, electric power plants, and all types of engines. Flight motion computers have wide applications for pilot training and other flight simulators.

Appearance (as manufactured): Software for missile design is physically indistinguishable from commercial software. It is contained on the same computer disks or CD-ROMs, etc. Missile analog/hybrid computers are custom electronics generally smaller than a breadbox. Flight motion computers are cabinets with commercial standard electronics racks. Missile software and specialized flight dynamics models can also be loaded on a pure digital, real-time computer (flight emulator). Real-time models can be used to replace the test article hardware in the loop.

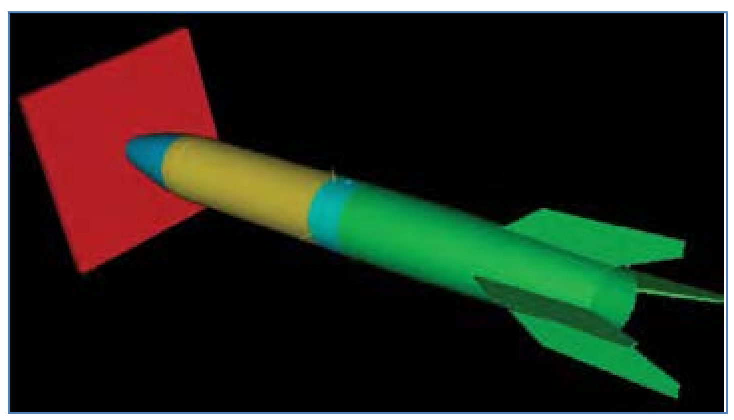


Figure 151: A computational model used for a simulation of a missile impact. (Sandia National Laboratories)

Appearance (as packaged): Custom electronics like analog/hybrid computers may be packaged in a variety of ways, including trunk containers used for shipping sensitive instruments and computer monitors. Flight motion computers are generally shipped like other electronic equipment. Other flight simulator hardware, including flight motion tables, may be packed in wooden crates for shipment. Models and real-time software look like any other software product and are packaged in cardboard boxes, possibly in shrink wrap (if commercial/new) or on unmarked standard transfer media, such as floppy disks, CD- ROMs, or ¼ inch magnetic tape cartridges.

16.B. Test and Production Equipment

None.

16.C. Materials

None.

16.D. Software

16.D.1. "Software" specially designed for modelling, simulation, or design integration of the systems specified in 1.A. or the subsystems specified in 2.A. or 20.A.

Technical Note:
The modelling includes in particular the aerodynamic and thermodynamic analysis of the systems.

•Australia	•Canada
•China	•France
•Germany	•India
•Israel	•Italy
•Japan	•Russian Federation
•South Africa	•Republic of Korea
•Sweden	•Switzerland
•United Kingdom	•United States

Global production



Nature and Purpose: Numerous design changes and flight environments can be investigated by using modelling, simulation and design-integration software, thereby reducing the expense of building, testing and redesigning actual hardware. This modelling capability dramatically decreases the cost and time required to develop a rocket or UAV. Computer-based models play a critical role in designing a rocket or UAV with desired range-payload performance capability. This is especially true when designing longer-range ballistic missiles. Using comprehensive software modeling to validate performance in the design stage leads to missiles with the most appropriate mission-related trade-offs, including range and payload capabilities.

Method of Operation: Most missile-design software models represent the physics of missile operation. Modern aerodynamic models offer a highly accurate treatment of flows internal and external to the missile and can be tailored to the specific missile geometry under evaluation. Thermodynamic models predict the aerodynamic heating and chemical reactions involved in thermal protection and missile propulsion, and the resulting transfer of heat into critical missile components. Finite-element models are now commonly used to design missile structures, as are models that combine guidance system hardware and missile flight control assemblies to test system level performance. An example of the output of a missile structure model is shown in Figure 151 above.

Typical Missile-Related Uses: Missile design software may be applied early in the design process to define overall configuration, thrust capabilities, aerodynamic flight loads, structural requirements, thermal insulation requirements and the guidance or control requirements of candidate design concepts, or

models. Subsystem hardware designs based on these models are tested, often with simulation software in-the-loop, to validate their capabilities and to refine the models to make them more design-specific.

Other Uses: Many of the more effective software models used to design rocket systems or UAVs are commonly used commercially. A popular structural model, NASTRAN, is used to design cars, trucks, passenger airplanes, and bridges, to cite a few examples. Thermodynamic codes such as SINDA are used to design satellites, electric power plants, and all types of engines.

Appearance (as manufactured): Software for missile design is physically indistinguishable from commercial software. It is contained on the same type of computer disks or CD-ROMs, etc. used for other software. Alternatively, missile software and specialized flight dynamics models can be loaded on a pure digital, real-time computer (flight emulator). Real-time models can be used to replace the test article hardware in the loop.

Appearance (as packaged): Software specially intended for designing aerospace and military products is often advertised as such. Models and real-time software are generally sold like any other software product and may be sold directly over the Internet. In the past, software was packaged in cardboard boxes, possibly in shrink wrap (if commercial/new) or on unmarked standard transfer media, such as floppy disks, CD-ROMs, or 1/4”magnetic tape cartridges.

Additional Information: High-speed digital computers can provide considerable leverage for developing real-time missile flight software. Some commercial computer standards are fast enough to support real-time missile performance simulations. The flight motion computer is the essential integrator that makes these commercial computers useful as emulators supporting missile software development and testing. Flight motion computers use specialized operating system software that enables them to act as simulation controllers and flight performance data loggers.

16.E. Technology

16.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or "software" specified in 16.A. or 16.D.

Nature and Purpose: Modelling, simulation and design integration technology is the knowledge or data necessary to design the software and computers needed for development of missiles, UAVs, and their subsystems and components. Modelling software can be used for engineering design, flight simulations, and as an aid in testing. Computer modelling involves sophisticated understanding of the physical domain being simulated. A designer must have thorough knowledge of the missile system or subsystem and then be able to convert knowledge of this subject into a computer model, i.e. software for mathematical calculations and producing numerical and graphical results. The accuracy of the model will improve as the designer gains experience through real-world experimentation and testing.

Method of Operation: Modelling, simulation and design integration technology is available in many forms. Technical assistance may consist of instruction provided by a person experienced in writing or modifying existing lower quality modelling, design or flight simulation software into that which will support rocket system or UAV design work, or a person who acts as a trainer in a classroom on or near the production site. A country may receive technical assistance from one or more consulting services that specialize in modelling or design software. Finally, a country may receive technical assistance by sending students to other countries possessing the technology to attend training and practice the skills necessary to build and operate the required systems. Any manuals and materials received during training may qualify as technical data.

Typical Missile-Related Uses: The technology required to develop rocket or UAV modelling or design software is partly specialized. Sounding rockets used in weather research are, with minor adjustments, ballistic missiles, and the modelling and design technology used in ballistic missiles and in sounding rockets is essentially the same.

Other Uses: Although the technology required to develop rocket or UAV modelling or design software is partly specialized, some may be generally applicable to many other purposes. UAV designers may use versions of the design and modelling software used in the civil and military aircraft industries.

Appearance (as manufactured): N/A.

Appearance (as packaged): N/A.

Category II - Item 17

Stealth

Category II – Item 17: Stealth

17.A. Equipment, Assemblies and Components

17.A.1. Devices for reduced observables such as radar reflectivity, ultraviolet/infrared signatures and acoustic sigantures (i.e. stealth technology), for applications usable for the systems specified in 1.A. or 19.A. or the subsystems specified in 2.A. or 20.A.

- Brazil
- China
- France
- Germany
- Greece
- Israel
- Italy
- Japan
- Netherlands
- Russian Federation
- South Africa
- Sweden
- Taiwan
- United Kingdom
- United States

Global production



Nature and Purpose: The need to protect missiles from detection, interception and destruction has led to the development of technologies to reduce their observables; when reduced observables are a primary design goal for a new vehicle, they are often referred to generically as "stealth" technology. Reflections and emissions are reduced or tailored through the use of carefully designed shapes and special materials. Other devices such as low-probability-intercept radar may be used. The objective is to make the object difficult to detect.

Method of Operation: Emissions and reflections are acoustic or electromagnetic in nature. Emissions are held to a minimum by any of a wide range of techniques such as frequency staggering, vibration isolation, shielding, masking, directing, and dampening.

Electromagnetic emissions and reflections occur in numerous frequency bands, including microwave (radar), infrared (IR), visible, and ultraviolet bands. Because a vehicle's signature varies significantly between and even within frequency bands, different methods must be applied across the spectrum. Emissions and reflections can be directed away from the observer and/or reduced in amplitude or altered in frequency response with the aid of carefully selected shapes and materials. This reduction is achieved by shaping, material, or devices for controlled emissions, reflectance, absorption, and second surfaces (added insulators and reflectors). These techniques or devices either conceal or disguise the true nature of the object from the observer or allow the vehicle to be detectable only at certain angles and for brief intervals, thereby delaying or avoiding detection and engagement.

Typical Missile-Related Uses: Stealth technology is used to make ballistic missiles, unmanned aerial vehicles (UAVs), including cruise missiles, and their payloads more difficult to detect, track, identify, and engage by defensive weapon systems. Most design elements of these systems are subject to treatment with stealth technology, including its basic shape, its structural components, its surfaces and leading edges, and its inlets and openings (Figure 152).

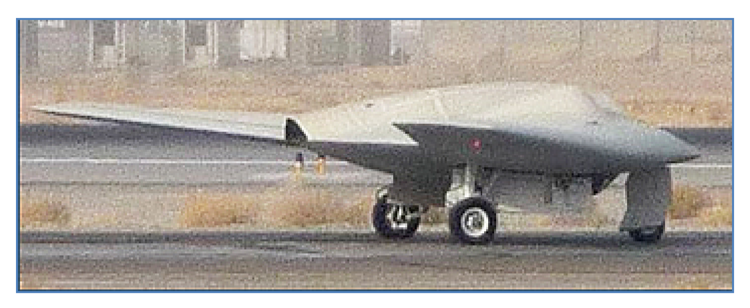


Figure 152: An image of a vehicle presumed to be a low observable UAV, taxing on a runway. (Aviation Week)

Other Uses: Most of the materials used for signature control were originally developed for military aircraft and are found on both fixed- and rotary-wing systems. Radar absorbent materials are also widely used in test facilities for radars. Modified versions of the materials and treatment techniques are found on some ships, submarines, and ground combat and tactical vehicles. Emission control materials technology also is used to control temperatures in satellites. Several devices can be used with communication gear to reduce detectability. There are commercial uses for some of the low cost, low performance materials for reducing electromagnetic interference and for reducing solar loading.

Appearance (as manufactured): Typical devices that result in reduced-observable treatments include, but are not limited to, the following categories:

There are two kinds of *conductive fillers*: conductive fibers, which look like very light whiskers 2 mm to 6 mm long, are made of carbon, metals, or conductive-material coated glass fibers; and conductive-material coated particles, which may look like colored sand.

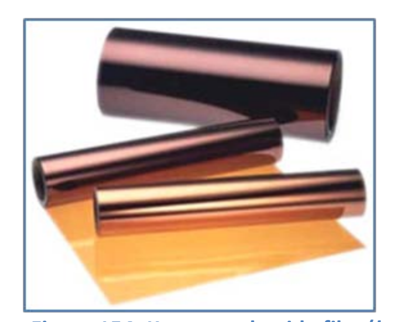
Small cell foams, both open and closed, are painted, or loaded, with absorbing inks and paints. These foams resemble flexible foam rubber sheets or air conditioning filters. They can be single-layered or noticeably multi-layered, with glue lines separating the strata. A ground plane, if applied, can consist of a metallic paint, a metallic sheet (aluminum foil or metalized thin plastic), or undetectable sprayed inks. Some manufacturers may mark the front of these foams with lettering saying “front” or with serial numbers if the ground plane is not obvious. Some foam may contain composite fiber to make them more rigid or even structural. Four such foams are shown in Figure 153.






Figure 153: Four radar absorbing material foams, from left: low-dielectric foam (epoxy); lightweight lossy foam (urethane); sprayable lightweight foam (urethane); and thermoplastic foam (polytherimide). (MTCR Equipment, Software and Technology Annex Handbook, Third Edition (May 2005))

Resistive Cards (R-Cards) consist of a sheet of fiber paper or very thin plastic (Figure 154) covered with a continuous coat of a conductive ink, paint, or extremely thin metallic film. The surface electrical resistivity of the coating may be constant or may vary continuously in one or two directions. The conductive ink versions are likely to be dark gray to black. The metallic coated versions may vary in color depending on both the specific metals used and the thicknesses involved, but black, yellow, green, and gold tints are common.



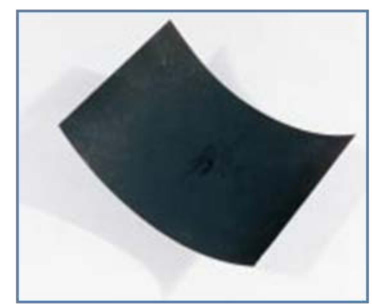


Figure 154: Kapton polymide film (*left*) is often used in the manufacture of resistive cards, such as that on the right. (Kapton film image credit: PSG Ltd)

Loaded ceramic spray tiles are sprayed-on and fired ceramic coatings heavily loaded with electrically conductive fillers or ferromagnetic particles. They are likely to range from dark gray to black in color. Depending on the specific filler and surface-sealing glaze used, they may range from smooth to abrasive in surface texture. Sprayed-on coatings may range from a few millimeters to tens of centimeters in thickness.

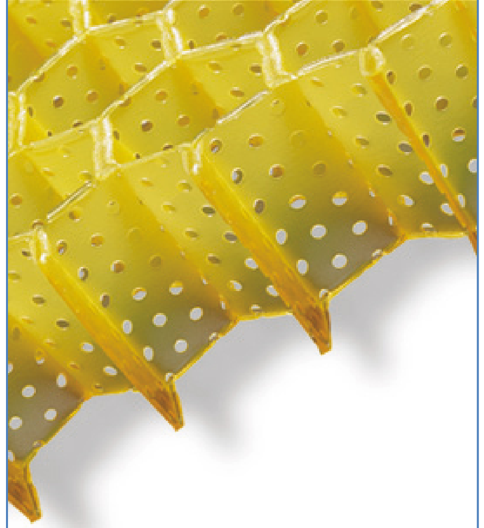


Figure 155: Absorbing Honeycomb has a variety of applications in defense and aerospace, including stealth. (Supracor)

Absorbing honeycomb is a lightweight composite with open cells normally 3 mm to 12 mm in diameter and 25 mm to 150 mm maximum thickness. It is treated with partially conductive inks, paints, or fibers. The honeycomb core may be shipped without being loaded, in which case it might be indistinguishable from materials used solely for structural purposes. The conductive inks and paints for subsequent loading are likely to come from an entirely different source than the core itself. Absorbing honeycomb is shown in Figure 155.

Appearance (as packaged): *Conductive fibers* vary from 2 mm to 6 mm in length and are usually packaged in plastic bags, vials, or jars. Their weight depends on the materials used. Fibers shipped before being chopped to their functional length may be in the form of conventional spools of textile fibers or in bundles 1 m to 2 m in length and 2 cm to 10 cm in diameter.

Foams come in sheets usually no larger than 1 m x 1 m, ranging from 6 mm to 200 mm in thickness, and weighing less than 40 g per square meter. They are packaged in cardboard boxes.

R-Cards are packaged in an envelope or box with a nonabrasive paper sheet between each card. Larger quantities may be shipped in rolls from 0.2 m to 1 m in length and 15 cm in diameter, inside desiccated tubes, or in cardboard boxes. *Loaded ceramic spray tiles* are usually bubble wrapped and packaged in cardboard boxes. *Absorbing honeycomb* is shipped in cardboard boxes.

17.B. Test and Production Equipment

17.B.1. Systems, specially designed for radar cross section measurement, usable for the systems specified in 1.A., 19.A.1. or 19.A.2. or the subsystems specified in 2.A.

- France
- Germany
- Israel
- Japan
- Russian Federation
- Republic of Korea
- Sweden
- United Kingdom
- United States

Global production



Nature and Purpose: Radar cross section (RCS) measurement equipment has been developed to evaluate, tailor, and reduce the RCS of missile systems in order to reduce detectability by air defense radars. RCS measurement equipment can be used in either indoor or outdoor ranges. Many of the ranges are usable for both military and commercial purposes. RCS measurement equipment can be used for evaluating material samples, missile components, scale models of missiles, and actual rocket systems or UAVs.

Method of Operation: An object under test, often called the target, is positioned or suspended in a test area with a few or no other objects in order to minimize sources of extraneous radar scattering. The target is then illuminated repeatedly by radar over a select range of radar frequencies of known amplitude, and the reflections are measured. The resulting data are evaluated, and radar reflectivity of the target as a function of frequency and viewing angle is determined.

Typical Missile-Related Uses: This equipment is necessary to determine, tailor, and reduce the radar signature of a rocket, UAV, or payload. These measurement systems also assess computer-modeled performance and ascertain whether the missiles have the desired reduced and tailored observables. Certain RCS equipment is used to characterize radar-absorbing materials.

Other Uses: RCS measurement systems can be used to determine the radar signature of any air, sea or land military vehicle. The measurements provide information that aids in tailoring or reducing the RCS. Indoor RCS measurement ranges can be adapted to measure antenna performance patterns for various commercial applications such as cell phones, automobile antennas, and satellite dishes.

Appearance (as manufactured): The basic elements of an indoor RCS test range (an example is shown in Figure 156) are radar source equipment, dual reflectors, target support devices, and bidirectional arches.

Radar Source Equipment: RF Equipment is a rack-mounted collection of electronic equipment that, when assembled, occupies the space of a filing cabinet and is used in all types of RCS measurement systems.

Up/down converters with feed horns provide radar illumination. To provide a wide range of frequencies, the conical feed horns vary in diameter from 1 cm to 100 cm in internal width. The feed horn length is generally two and a half times the internal width. They are metal lined and have provisions for attaching a coaxial cable or waveguide on the rear end. In RCS measurement systems, radar feed sources can be replaced by a radar source from a commercial radar system (e.g., marine radar). Network analyzers can measure absorption and reflection, and are commonly used commercially to develop antennas and electromagnetic interference shielding materials. RF cabling is low-loss coaxial cabling and is required for connecting the components. These cables vary in length but are normally 1 cm to 2 cm in diameter and have a metal mesh outer surface.

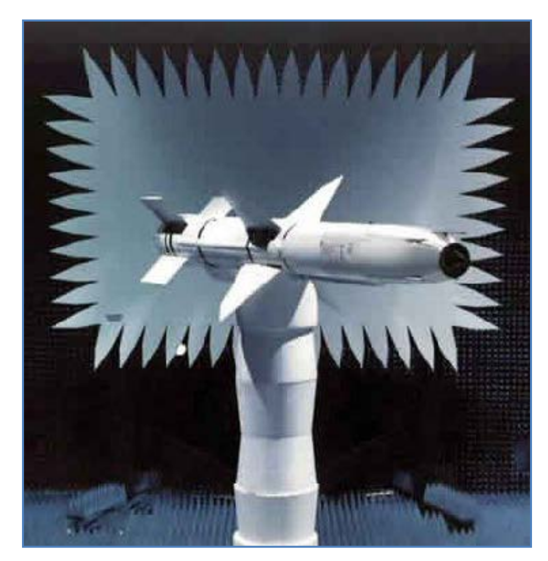


Figure 156: A target missile in the Bistatic Anechoic Chamber (BAC) RCS measurement compact range. (U.S. Navy)

Dual Reflectors: Cassegrain measurement systems use two large plates or dishes of different dimensions as reflectors; they can be circular, elliptical, or rectangular. The plates may have calibration marks on several portions of the surfaces and may be painted. Reflectors may be assembled from pieces and may have rolled or serrated edges. For measuring the RCS of a typical cruise missile, the two reflectors are 2 cm to 5 cm in thickness, and their major axes are 4 m and 5 m in length. These reflectors create a measurement "sweet spot" 2 m in diameter. This type of system is almost invariably used for indoor measurements. It should be noted that a measurement system could be devised using a single reflector.

Target Support Devices: These devices hold the target off the floor or ground and in the radar illumination; they need to be as imperceptible to radar as possible. Styrofoam columns, metal blades coated with radar absorbing material (RAM), and puppet strings from overhead mounts are common methods of supporting and suspending targets to be measured. The Styrofoam columns may range from 2 m in height and 0.5 m in diameter to 5 m in height and 2 m in diameter. Their horizontal cross-section may be round (with or without taper), square, triangular, or diamond-shaped. The metal blades, or pylons, may range from 2 m to 40 m in length and be 5 cm x 30 cm at the top; short pylons are 50 cm x 90 cm at the bottom, and tall pylons are 2 m x 8 m at the bottom. Both Styrofoam columns and pylons can be mounted on a mechanism that tilts them forward. Rotating interfaces can also turn the Styrofoam column and target. Sets of three to five Styrofoam columns mounted on a common turntable can be used to support and rotate a target. Some pylons also have a rotating interface with the target at the top.

Bidirectional Arches: Another approach to measuring missile RCS is to use a bidirectional arch, which can be made out of plywood, fiberglass, or metal. An electric motor drive system is used to relocate the feed horns along the arch. Custom cabling links the arch to a control computer (normally a PC with a keyboard and monitor) and the feed controls. A test article, with its surface perpendicular to the plane defined by the arch, is placed at the center of the arch. The articles are typically 0.3 m to 1.0 m on a side. The

calibration reference is a flat, smooth metal plate the same size as the test article.

Appearance (as manufactured): Transmission/reflection tunnel RCS measurement systems look like large, sheet metal, air vent ducting. They have two matching metal feed horns with coaxial cabling or waveguides leading to the radar source and detector measurement electronics. They are controlled by a computer that looks like any PC with a keyboard and a monitor. There may be radar-absorbing foam (normally medium blue or black in color and spiked on the surface) inserted in portions of the ducting. Direct illumination indoor systems and bounce range outdoor systems use conventionally shaped, parabolic radar reflectors ranging in size from a few centimeters up to 10 m in diameter.

Appearance (as packaged): Radar ranges are seldom shipped as one piece; rather, they are assembled onsite from many components. There are no unique packaging requirements for this equipment beyond those of the industry standard for rack-mounted electronics and commercial computer components. Some of the components (such as the Cassegrain reflectors) can be fairly large and require special crates. Styrofoam target supports are delicate and must be packaged to prevent denting.

17.C. Materials

17.C.1. Materials for reduced observables such as radar reflectivity, ultraviolet/infrared signatures and acoustic signatures (i.e. stealth technology), for applications usable for the systems specified in 1.A. or 19.A. or the subsystems specified in 2.A.

Notes:
1. 17.C.1. includes structural materials and coatings (including paints), specially designed for reduced or tailored reflectivity or emissivity in the microwave, infrared or ultraviolet spectra.
2. 17.C.1. does not control coatings (including paints) when specially used for thermal control of satellites.

Nature and Purpose: The need to protect ballistic missiles and UAVs (including cruise missiles) from detection and destruction has led to the development of technologies to reduce their observables through the use of carefully designed special materials to absorb radar energy or shield or mask the vehicle from the radar energy or other detection systems that may be in use. The objective is to make the missile or UAV difficult to detect.

Method of Operation: Emissions are also held to a minimum by other techniques, such as shielding, masking, directing and dampening. Emissions and reflections can be affected with the aid of carefully selected materials applied to the airframe. This reduction is achieved by shaping material for controlled emissions, reflectance, absorption and second surfaces (added insulators and reflectors). These techniques or devices either conceal or disguise the true nature of the object from the detection devices or allow the vehicle to be detectable only at certain angles and for brief intervals.

Typical Missile-Related Uses: Stealth technology is used to make ballistic missiles, UAVs (including cruise missiles) and their payloads more difficult for defensive weapon systems to detect, track, identify and engage. Most design elements of a missile are subject to treatment with stealth technology, including its basic shape, its structural components, its surfaces and leading edges and its inlets and openings.

Other Uses: Most of the materials used for signature control were originally developed for military aircraft and are found on both fixed- and rotary-wing systems. Modified versions of the materials and treatment techniques are found on some ships, submarines and ground vehicles. Emission control materials technology also is used to control temperature in satellites. There are commercial uses for some of the low-cost, lower performance materials for reducing electromagnetic interference and for reducing solar loading.

Appearance (as manufactured): Typical materials for reduced-observable treatments include, but are not limited to, the following categories:

Sprays include conductive inks or paints, normally containing silver, copper, zinc, bronze, or gold as the base ingredient. They appear black, metallic gray, copper, bronze, or gold in color.

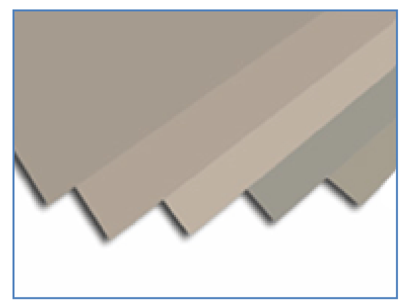


Figure 157: Custom engineered epoxy resin Mag RAM. (MSM Industries)

Magnetic Radar Absorbing Material (commonly known as Mag RAM) as applied to vehicles, may appear in forms such as surface coverings, molded edges, or gap fillers. It consists of very fine grained ferromagnetic or ferrite particles suspended in a variety of rubber, paint, or plastic resin binders. It may be applied as sprays, sheets, molded or machined parts, or putties. Because of the general colors of typical binders and ferromagnetic particles, the natural colors of Mag RAM range from light gray or brown to nearly black (Figure 157); however, with additional pigments added for other reasons (e.g., visual camouflage or manufacturing/maintenance-aid coding), almost any color is possible. Thin films of plastic or paper material may cover one or both sides of sheets for identification coding or maintaining pre-application surface cleanliness. Sheet thickness may range from less than a millimeter to several centimeters. The density of the material is likely to range from 50% to 75% of solid iron.

Transparent Radar Absorbent Material (T-RAM) looks like sheet polycarbonate. It is normally 75% to 85% transparent in the visible spectrum. Absorbing materials can vary from fibers or spheres spread throughout the material to thin coatings, which look like yellow/green metallic window tinting.

Infrared (IR) Treatments usually consist of paints and coatings. Often these coatings are customized to tailor reflectance and/or radiation of IR energy. Because of the wide spectrum (0.8 microns to 14.0 microns wavelength) of IR energy and the variety of applications, IR coatings may either be reflective (low emissivity) or designed to absorb (high emissivity). Coatings used for IR treatment include specially designed military paints in camouflage colors or commercial paints designed to reflect solar heat. Some of these products have a noticeable metal content in the paint/binder due to the IR pigments used. Others

are designed to have high emissivity and as such, contain pigments that absorb IR. These high emissivity coatings contain carbon-based or other highly emissive particle-based pigments (normally nearly black). In either case, these IR pigments are sometimes shipped separately from the paint/binder.

Appearance (as packaged): Spray paints and inks are generally shipped in standard-size cans. The cans may be in boxes containing desiccants, or the pigments and binders may be shipped separately. Pigments are shipped in jars, plastic bags or cans, and the binders are shipped in cans or drums. Most are highly toxic or caustic materials until applied and cured.

Mag RAM may be shipped in sheets, uncured slurries and finished parts, or in raw material form (particles, binder and polymerization-activator all shipped separately).The particles would most likely be shipped in a very fine powder or short fiber form but possibly also immersed in a hydrophobic fluid to prevent rusting. It may be shipped in sheets up to a few meters in length and width. Sheet thickness may range from less than a millimeter up to tens of centimeters. It may be shipped several layers deep on flat pallets or as a rolled sheet inside a cardboard tube. If shipped as formed parts, it may be in rectangular cardboard or wooden boxes as large as 0.1 m x 0.1 m x 2.0 m or as small as 20 cm x 20 cm x 20 cm.

T-RAM is packaged like sheet polycarbonate or like a window or canopy part. It can have an adhesive protective paper applied to the outside. If shipped in smaller pieces, it would be boxed.

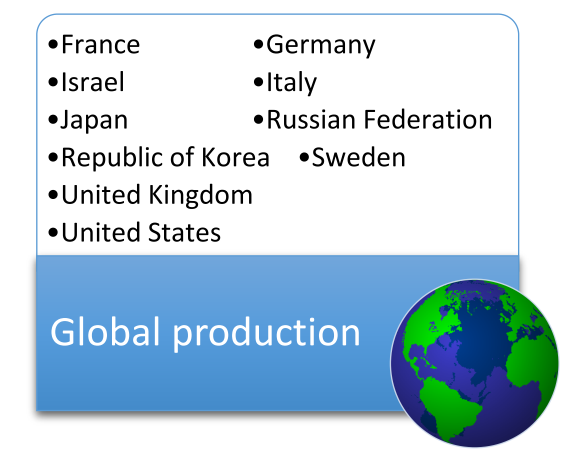
IR thermal paints and coatings are usually packaged in cans like any paint product. IR paint pigments can be packaged in cans, vials or plastic bags.

17.D. Software

17.D.1. "Software" specially designed for reduced observables such as radar reflectivity, ultraviolet/infrared signatures and acoustic signatures (i.e. stealth technology), for applications usable in the systems specified in 1.A. or 19.A. or the subsystems specified in 2.A.

Note:
17.D.1. includes "software" designed for analysis of signature reduction.

Nature and Purpose: Designing and producing materials for, and systems with, signature reduction normally requires software and databases for analyzing these materials and systems. Software and databases specially designed for analysis of signature reduction are controlled. These databases and software will include data or functions essential to analysis of the signature reduction capability of



systems and materials.

Method of Operation: Emissions and reflections may take many forms such as acoustic, radio frequency (e.g. radar), visible light, or infrared energy. Software can be used to mathematically model these physical effects as a function of the shape of an object and its surface properties. Materials of construction, including coatings, affect surface properties. Controlled software and/or databases contain information or methodologies specially designed for analysis of emissions and reflectance (signatures). Software and databases may be used to analyze developmental or existing systems in order to determine effectiveness of the materials and devices already incorporated as well as to determine what areas need improvement.

Typical Missile-Related Uses: These items are used to analyze airframe shape and materials for applications to ballistic missiles and UAVs (including cruise missiles), in order to select signature reducing treatments or to identify hot spots (potential areas for improvement). Similarly, these items may be used to evaluate the signature of systems, quantify performance of designs and material choices in systems, and evaluate areas for improvement.

Other Uses: The same or similar software and database items may be used to analyze and design for signature reduction on many military articles – including ground vehicles, manned aircraft, and ships. Software intended to model similar kinds of physical effects can be used for analysis of energy-management systems for satellites and buildings, in particular infrared emissions related to thermal controls. Passive and active detectors used for security alarm systems and autonomous systems such as self-driving cars also may require analysis using similar software and databases.

Appearance (as manufactured): Software for signature reduction design tools might be packaged on floppy discs, tapes, USB flash drives, and compact discs. Alternatively, a computer network can be used to distribute software and its documentation electronically.

Appearance (as packaged): Historically, software on floppy discs, tapes, USB flash drives, and compact discs has been packaged in any of a wide variety of packets, pouches, mailers, or boxes. Software may also be packed with related hardware. In the Twenty First Century, it is very likely for software to be transferred directly over the internet.

Additional Information: Analysis for the sake of reduced observables is more of a niche activity than other types of analysis such as finite elements (structures) and fluid flow (aerodynamics etc.). In the absence of widespread non-military end-uses, software for reduced observables is less likely to be advertised and sold commercially.

Each spectrum or portion thereof may have its own specific design software. Many countries and defense contractors have developed computer codes for one-, two- or three-dimensional analysis and design optimization. In the radio frequency (RF)/radar spectrum, any code that can model antennas or radomes can be modified and used as a radar cross section tool. As a rule of thumb, any software code name that includes the letters SIG, RF or RCS, should be regarded as suspect RCS code. Codes that run on personal computers can provide useful design guidance. When exotic materials and complex shapes come into play, supercomputers and specially designed codes become particularly valuable.

The key elements of RCS design codes involve the ability to define a vehicle surface profile within an adequate margin (which can be as small as 1/20 of a wavelength of the highest frequency of interest); the ability to represent very small elements of the surface as vectors; and the ability to calculate the mathematics associated with magnetic permeability and electrical permittivity. These items indicate the value of general purpose codes and machines capable of rapidly inverting and manipulating very large matrices of numbers.

IR thermal codes specialized for reduced observables may be less readily available or mature, but there are commercial codes available that can be used or modified for military applications. These codes include those used for thermal quality control. As in RF, a code capable of vector representation of the size and orientation of surface elements is a critical starting point. Codes estimating the atmospheric transmission of IR radiation at different altitudes, seasons and types of gaseous environments are used in the design process. Codes useful for determining heat transfer in aircraft are essential, in order to determine surface temperatures and heat fluxes resulting from the operation of engines and other internal subsystems. Codes for determining plume temperature from the volume of combustion products passing through the tailpipe and expanding and dissipating in the atmosphere are typically involved. Plume modeling, which can be done for the exhaust gases of either rocket propulsion or air-breathing propulsion, often involves engine deck codes but goes beyond their use for determining propulsion performance. Codes that use material emissivity and bidirectional reflection coefficients of materials as inputs may indicate their potential use in IR signature control design.

17.E. Technology

17.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment, materials or "software" specified in 17.A., 17.B., 17.C. or 17.D.

Note:
17.E.1. includes databases specially designed for analysis of signature reduction.

Nature and Purpose: Stealth technology is a relatively new science and not widespread. Technology, as used in this section, is the provision of significant aid or assistance to a country engaged in developing the means to reduce the signatures of UAVs (including cruise missiles) and possibly ballistic missiles. As used in this section, transferring specialty coatings such as T-RAM, Mag RAM, conductive fibers or other low-observable materials obviously would be critical transfers, as would transferring the technology to produce such materials. Providing a country with the technology to produce RCS test equipment or information needed to construct an RCS test range would be a transfer of controlled technical information.

Method of Operation: Technical assistance is available in many forms. Technical assistance may consist of instruction provided by a person experienced in one or more controlled subjects, such as low-observable technology, who acts as a trainer in a classroom on or near the production site. A country may receive technical assistance from one or more consulting services that specialize in a particular production skill. A country may also receive technical assistance with procurement of technical equipment, machines or material, or in the identification of companies and materials to acquire. Finally, a country may receive technical assistance by sending students to other countries possessing the technology to attend training and practice the skills necessary to build the required systems.

Typical Missile-Related Uses: With limited exceptions, technical assistance required to build stealth-material-producing equipment and test facilities are used only for those purposes.

Other Uses: N/A

Appearance (as manufactured): N/A

Appearance (as packaged): N/A

Category II - Item 18

Nuclear Effects Protection

Category II – Item 18: Nuclear Effects Protection

18.A. Equipment, Assemblies and Components

18.A.1. "Radiation Hardened" "microcircuits" usable in protecting rocket systems and unmanned aerial vehicles against nuclear effects (e.g. Electromagnetic Pulse (EMP), X-rays, combined blast and thermal effects), and usable for the systems specified in 1.A.

- France
- Israel
- Japan
- Russian Federation
- Sweden
- United Kingdom
- United States

Global production



Nature and Purpose: Space and sub-space environments require specialized technologies that reduce the risks of exposure to ionizing radiation from energetic charged particles and X-rays. Ionizing radiation causes two critical damage mechanisms in microcircuits and can impact their ability to function properly. A cumulative effect of radiation, known as Total Ionizing Dose (TID), relates to the build-up of a permanent electrical charge in a circuit, which disrupts its ability to respond or causes it to fail completely. The scale of this build-up depends on the extent to which the circuit is exposed to radiation. The second effect, due to charge deposited by a single ionizing particle, is known as a Single Event Effect (SEE). Some SEEs such as Single-Event Transient (SET) and Single-Event Upset (SEU) are temporary and can be recovered. Others such as Single-Event Latch-up (SEL) lead to permanent damage. The sensitivity of a device to SEEs depends on how quickly the radiation is delivered to the circuit (the number of events/particles per cm^2). One way to protect circuits from such effects is to make them intrinsically resistant to TID and SEEs, a process known as 'hardening'.

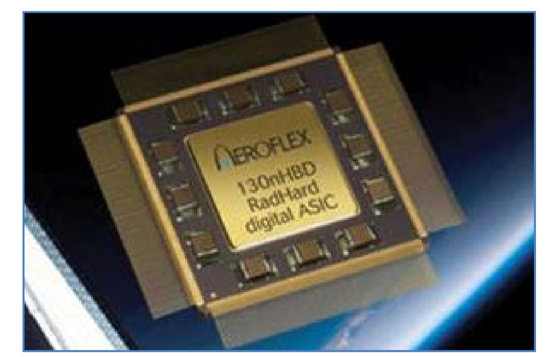


Figure 158: A radiation hardened application specific integrated circuit (ASIC) designed for high reliability and radiation-intense applications. (Aeroflex)

Method of Operation: Hardened microcircuits (Figure 158) are similar in operation and appearance to regular microcircuits. Mitigation strategies to reduce TID and SSE effects are known as Radiation-Hardening-By-Process (RHBP) and Radiation-Hardening-By-Design (RHBD) techniques. RHBP can be achieved by modifying doping profiles in devices and substrates and optimizing the deposition processes for insulators. RHBD techniques include register redundancy, latch-level redundancy, OR

logic gate feedback, and other layout circuitry. Devices designed and produced with these mitigation strategies greatly increase the cost of a hardened microcircuit and also tend to lower digital operating rates.

Typical Missile-Related Uses: Radiation-hardened microcircuits used in ballistic missiles are designed to operate in a nuclear environment. Unmanned aerial vehicles (UAVs), other than some cruise missiles, are generally not protected from ionizing radiation because their survivability has not been considered.

Other Uses: Radiation-hardened devices are used in spacecraft for long-duration missions which include telecommunications equipment, scientific meteorological satellites, space and planetary probes. Ground based hardened microcircuits are also used in high-radiation environments such as safety, instrumentation, control, detectors, and robotics for nuclear reactors and high-energy physics particle accelerators.

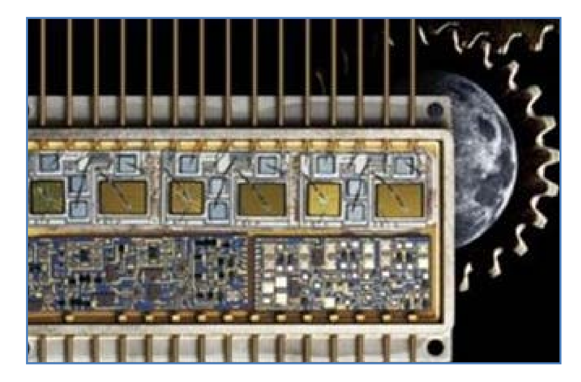


Figure 159: A radiation hardened motor driver designed for radiation-intense military and aerospace applications. (Aeroflex)

Appearance (as manufactured): Hardened electronic component devices and their assemblies are typically mounted in hermetically sealed metal or ceramic packages with surface-mounted devices common in high-density assemblies (Figure 159). They look like commercial devices, but they may have part numbers identifying them as hardened.

Appearance (as packaged): Electronic assemblies and components are typically shipped in plastic bags marked to designate an electrostatic sensitive device. They are cushioned in rubber foam or bubble wrap for shock protection and packed inside cardboard boxes.

18.A.2. 'Detectors' specially designed or modified to protect rocket systems and unmanned aerial vehicles against nuclear effects (e.g. Electromagnetic Pulse (EMP), X-rays, combined blast and thermal effects), and usable for the systems specified in 1.A.

Technical Note:
A ´detector´ is defined as a mechanical, electrical, optical or chemical device that automatically identifies and records, or registers a stimulus such as an environmental change in pressure or temperature, an electrical or electromagnetic signal or radiation from a radioactive material. This includes devices that sense by one time operation or failure.

Nature and purpose: As noted above, one mechanism to protect circuits in harsh and nuclear intense operating environments is to make microcircuits intrinsically resistant to the total dose of ionizing radiation. Another technique is to use radiation detectors capable of sensing radiation dose rates in these environments, and/or recognizing and registering environmental changes resulting from nuclear events. These detectors subsequently turn off the circuit power or trigger protection devices that respond to these conditions.

Method of operation: Radiation detectors are relatively simple devices that sense an increase in current caused by radiation. If the radiation level reaches and surpasses a critical threshold, the detectors issue a control signal to protection circuitry. The protection mechanism either shunts currents away from sensitive devices or turns off the equipment to avoid burn-out. The detectors usually have a test input to activate the detector during construction or maintenance activities to verify operation. They must usually be able to withstand radiation effects (e.g. they must be re-usable), and must have the capacity to issue protection commands immediately before damage occurs in the microcircuits.

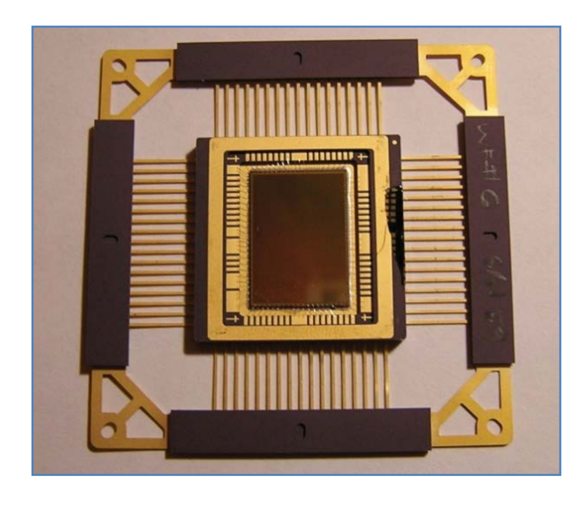


Figure 160: A radiation-hardened detector. (U.S. Air Force)

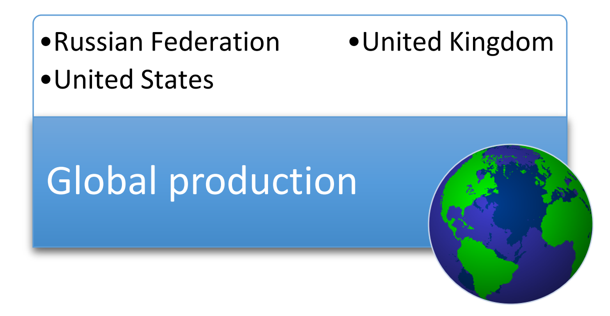
Typical Missile-Related Uses: As with hardened microcircuits, radiation detectors are used in space launch vehicles and ballistic missiles intended to operate in the nuclear-intense space and sub-space environments. Protecting unmanned air vehicles (UAVs) from ionizing radiation is generally not required because they are usually more vulnerable to blast overpressure, which would impact a UAV system at greater distances from a nuclear explosion than radiation.

Other uses: Radiation detectors are used in the same high-reliability applications and nuclear-intense environments as hardened microcircuits. These include long-duration military, telecommunications, and scientific missions. They are also critical electronic components on meteorological satellites, space stations, and planetary probes. Detectors are also used in nuclear reactor safety applications; instrumentation, control, and robotics systems.

Appearance (as manufactured): Radiation detector circuits may consume about a dozen square centimeters of circuit board space. Alternatively, the detector can be a single microcircuit with external select components as shown in Figure 160.

Appearance (as packaged): Electronic assemblies and components are typically shipped in plastic bags marked to designate an electrostatic sensitive device. They are cushioned in rubber foam or bubble wrap for shock protection and packed inside cardboard boxes.

18.A.3. Radomes designed to withstand a combined thermal shock greater than 4.184 x 10^6 J/m^2 accompanied by a peak over pressure of greater than 50 kPa, usable in protecting rocket systems and unmanned aerial vehicles against nuclear effects (e.g. Electromagnetic Pulse (EMP), X-rays, combined blast and thermal effects), and usable for the systems specified in 1.A.



Nature and Purpose: Radomes are non-metallic shell structures that protect antennas from the environment while allowing transmission of radio frequency signals with minimal signal loss and distortion. They are usually made of an insulating material. Many ground installations use radomes, and the nose tips of passenger airliners are radomes. Only specialized radomes are controlled in MTCR Item 18.A.3., namely those intended for a nuclear effects environment, sometimes but not always designed for high-speed flight. Controlled radomes are typically made of special materials such as ceramics or silicon phenolic. The criteria outlined in Item 18.A.3. limit control to radomes intended to survive a severe heat and pressure environment.

Method of Operation: Radome materials are selected for their strength and signal transparency in the frequency bands of interest throughout the expected temperature range. Flight radomes are usually shaped to enhance the aerodynamic performance of the vehicle and to avoid undue disturbances of the signal from prismatic, or lens, effects. Correctly designed radomes allow the enclosed antenna to transmit and receive signals through the radome with minimal distortions.

Typical Missile-Related Uses: The nuclear environments envisaged in Item 18 limit the missile-related uses of these radomes to some cruise missiles and to the Re-entry vehicles (RVs) carried by short- to intermediate-range ballistic missiles. One use of such radomes is to protect guidance seekers installed in the nose of RVs as they guide the RVs to their targets. Longer-range missiles reenter the atmosphere too fast for nose mounted radomes to survive. For these RVs, radomes (windows) may be located further back on the RV body. MTCR-controlled radomes are not generally of interest for UAV systems other than cruise missiles because most UAVs cannot survive the specified nuclear effects. Certain ground installations can

use controlled radomes if it is desirable for them to be hardened to the specified nuclear effects. For example, non-flight radomes meeting the criteria in Item 18.A.3. could be used to protect antennas at missile silos or command posts designed to survive nuclear attack.



Figure 161: *Left*: a selection of aerodynamic radomes (Northrop Grumman). *Right*: radomes similar to those that might be used to protect RV seekers on reentry. (American Technology & Research Industries)

Other Uses: Radomes designed for nuclear survival have few (if any) commercial uses

Appearance (as manufactured): Radomes used to protect nose-mounted sensors in RVs or missiles are conical or ogive in shape, as shown in Figure 161. They range in size depending on the size of the RV or missile to which they are attached, and can be as small as 30 cm, and as large as 2 m or more in diameter and length. The materials are basically dielectrics in solid laminates or sandwiched foam formed as a single, one-piece molded radome. A thin wall, dielectric space frame (DSF) radome, usually 0.1 cm or less in thickness, may be used for small antennas. A solid laminate-wall DSF radome typically is 0.25 cm in thickness. For two-layer, sandwich DSF radomes, a foam layer is added to the inside of the thin wall radome. The foam thickness is chosen primarily for thermal insulation and resistance to thermal shock loads of 100 cal per cm^2 (the same energy per area as 4.184×10^6 J/m^2 in the control language). A composite sandwich, foam-core wall radome is the most expensive design and provides the strength to withstand peak over-pressure loads greater than 50 kPa (about 50 percent above atmospheric pressure). A sandwiched foam-core wall is one-quarter wavelength thick for the highest radio frequency signal.

Appearance (as packaged): Radomes are shipped in wooden crates that have contour braces within them to support their thin wall structure. Radomes have closure frames mounted on their aft flanges to maintain structural rigidity in transit and are wrapped in polyethylene bags. Crates can use either formed wooden bulkheads for contour bracing or polyurethane foam, to support the radome.

18.B. Test and Production Equipment

None.

18.C. Materials

None.

18.D. Software

None.

18.E. Technology

18.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment specified in 18.A.

Nature and Purpose: Nuclear effects protection "technology" is the knowledge or data needed to increase the survivability of the electronic systems in missile systems in nuclear environments while they are en-route to a target or when they may be exposed to these environments while stored.

Method of Operation: Nuclear effects protection "technology" is available in many forms. "Technical assistance" may consist of instruction provided by a person or organizations experienced with developing radiation-hardened microcircuits or nuclear-event (X-ray, EMP, thermal effects) detectors suitable for ballistic missiles and who acts as a trainer in a classroom on or near the development or production site. A country may receive "technical assistance" from one or more foreign entities that possess the design and development facilities needed to provide hands-on experience to develop or operate the desired technology. A country may also receive procurement assistance in the form of help in obtaining the equipment, machinery and materials or guidance as to what items should be acquired. Any manuals and materials received during training may qualify as "technical data".

Typical Missile-Related Uses: The "technology" included in this section is used to protect electronic components within a ballistic missile from the radiation effects of nuclear detonation.

Other Uses: Nuclear effects protection "technology" is used in other industries that specialize in nuclear-hardened equipment. Ground based hardened microcircuits are in high-radiation environments such as safety, instrumentation, control, detectors, and robotics for nuclear reactors and high-energy physics particle accelerators.

Appearance (as manufactured): N/A.

Appearance (as packaged): N/A.

Category II - Item 19

Other Complete Delivery Systems

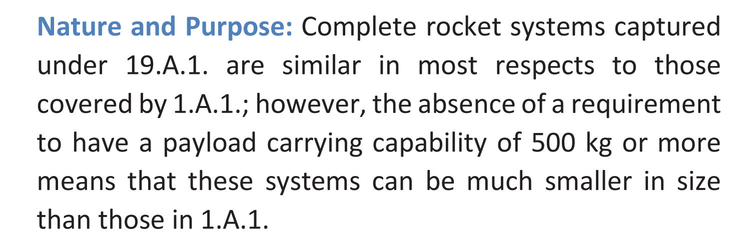
Category II – Item 19: Other Complete Delivery Systems

19.A. Equipment, Assemblies and Components

19.A.1. Complete rocket systems (including ballistic missiles, space launch vehicles, and sounding rockets), not specified in 1.A.1., capable of a "range" equal to or greater than 300 km.

- Australia
- Brazil
- Bulgaria
- China
- Czech Republic
- Egypt
- France
- Germany
- India
- Iran
- Israel
- Italy
- Japan
- Libya
- North Korea
- Pakistan
- New Zealand
- South Africa
- Russian Federation
- Republic of Korea
- Spain
- United Kingdom
- United States

Global production



Nature and Purpose: Complete rocket systems captured under 19.A.1. are similar in most respects to those covered by 1.A.1.; however, the absence of a requirement to have a payload carrying capability of 500 kg or more means that these systems can be much smaller in size than those in 1.A.1.

Evaluation of systems covered under this Item must take into account the ability to trade off payload and range. This inherent capability may differ significantly from manufacturers' specifications or intended operational concepts.

These systems are MTCR-controlled because of their suitability for delivering chemical and biological weapons, which are not constrained to substantial minimal weights as nuclear weapons are by critical mass.

Method of operation: These systems operate in precisely the same manner as larger rocket systems, and usually consist of the four basic elements (a payload or warhead, a propulsion subsystem, a guidance and control subsystem, and an overall structure). Ballistic missiles in this category have the same operating characteristics as larger items detailed in 1.A.1. Both categories might have one or more stages, and they might use solid or liquid propellants, or a hybrid of the two. Compared to their larger 1.A.1. counterparts, missiles controlled by 19.A.1. are more likely to be launched from aircraft. The latter launch method occurs at a high altitude to reduce atmospheric drag, which becomes more significant as missiles and SLVs are made smaller.

Typical Missile-Related Uses: Ballistic missiles are used to deliver a weapons payload to a defined target. Potential low-mass payloads include chemical and biological weapons. Many existing missiles fall short of the 300-km range capability for payloads exceeding 500 kg (thus not controlled by Item 1.A.1), but quite often missiles in this class can be re-purposed to send smaller payloads (<500 kg) to distances greater than

300 km. This shows the importance to take into account the ability to trade off payload and range when evaluating systems covered under this Item.

Space launch vehicles and sounding rockets are used to place satellites in orbit or to gather data in the upper atmosphere. Starting in the 1950s, sounding rockets were used to gather scientific data in the upper atmosphere. In the Twenty-first Century, there has been a renewed interest in sending small science payloads on suborbital trajectories, for the purpose of obtaining multiple minutes of free-fall (exposure to microgravity). Similarly, there has been a renewed interest in small space launch vehicles (SLVs) for delivering small satellites to orbit. As of circa 2017, multiple private commercial ventures around the world have sought to develop such smaller SLVs, with the expectation that there will be customers for dedicated launches for small payloads such as cubesats (<10 kg), for example.

Other uses: N/A

Appearance (as manufactured): Complete rocket systems in this category are very similar in appearance to those in 1.A.1., but on a smaller scale. They are large, long, narrow cylinders which, when assembled, typically have dimensions of about 5 m in length, 0.5 m in diameter, and a 1,500 kg weight with a full load of propellant. Figure 162 provides a representative example of a sounding rocket covered by 19.A.1. Missiles covered under this control criterion might have multiple stages, or only one stage. They are relatively heavy when solid propellants are used, or lightweight when unfueled if designed for liquid propellants.



Figure 162: A large Category II sounding rocket, capable of delivering a 250 kg payload to a range of 400 km. The rocket's solid propellant motor, with steel casing, is surrounded by four honeycomb tail fins with titanium alloy leading edges. (JAXA)

Appearance (as packaged): The major components of rocket systems are often shipped in crates or sealed metal containers to an assembly facility near the launch location, where they are assembled and tested for operational readiness. However, smaller launch vehicles are more likely than large ones to be shipped fully assembled. A specific example is that of mobile ballistic missiles, which can be fully assembled and stored in a horizontal position in a mobile transporter-erector-launcher (TEL) and moved to the launch point when required. Small missiles and SLVs might be transported by aircraft, and/or launched from aircraft.

19.A.2. Complete unmanned aerial vehicle systems (including cruise missiles, target drones and reconnaissance drones), not specified in 1.A.2., capable of a "range" equal to or greater than 300 km.

Nature and Purpose: UAV systems covered by Item 19.A.2. are far more diverse in nature than those in Item 1.A.2. owing to the absence of a payload carrying capability requirement of 500 kg. This category of UAV consequently includes a number of smaller long range endurance and Medium Altitude Long Endurance (MALE) UAVS that have far lower maximum take-off weights (ranging between less than 50 kg and 1,500 kg) than the large High Altitude Long Endurance (HALE) systems that meet the criteria in 1.A.2.

Evaluation of systems covered under this Item must take into account the ability to trade off payload and range. This inherent capability may differ significantly from manufacturers' specifications or intended operational concepts. These systems are MTCR-controlled because of their suitability for delivering chemical and biological weapons, which are not constrained to substantial minimal weights as nuclear weapons are by critical mass.

As with larger MTCR Category I UAV systems, UAVs covered by 19.A.2. are air-breathing vehicles powered by small turbine or piston engines that drive either free or ducted propellers. Long range, endurance and MALE UAVS have typical operating altitudes of between 5,000 m and 8,000 m, and maximum endurance of between 12 hrs and 48 hrs.

Cruise missiles are distinguished from most other UAVs by their use as weapon delivery platforms and by flight trajectories that often minimize their vulnerability to defenses. Further, cruise missiles do not have any designed recovery means (e.g., landing gear, parachutes, etc.). Cruise missiles can fly at almost any speed, but they are usually powered by small jet engines that typically operate at high subsonic speeds (less than 900 km/hr). A Category II anti-ship cruise missile is shown in Figure 163.

Method of operation: UAV systems can be controlled in flight by an onboard navigation system, which can fly a pre-programmed route following waypoints. Alternatively, the course of the UAV system can be adjusted in-flight with commands from a ground-based system, relayed via the onboard data link. UAV ground stations include a flight control system (usually a joystick console), and a series of display monitors and recording equipment. Meanwhile, an onboard flight control system maintains the UAV system in controlled flight, adjusting the control surfaces to maintain the desired flight path.



Figure 163: A category II anti-ship cruise missile. (MTCR Equipment, Software and Technology Handbook, Third Edition (May 2005))

Cruise missiles in this category operate exactly as those detailed in 1.A.2.: most contain a sensor system that guides them towards their targets by using terrain features or target signatures. Cruise missiles increasingly use inertial navigation systems, updated by Global Navigation Satellite System (GNSS) receivers in addition to, or instead of, terrain-aided navigation systems to guide them to the vicinity of the target. These missiles can be launched from Transporter-Erector-Launchers (TELs), as well as from ships, submarines or aircraft.

As with other UAVs described in 1.A.2., those systems covered by 19.A.2. are usually equipped with several types of payloads, including sensor equipment, contain avionics and data links, and are supported by a ground control component. In operations, the collection of the UAV flight vehicle (with payloads and avionics) and its ground support component is often referred to as an Unmanned Aerial System (UAS). One of the key differences between these Category II UAVs and the larger Category I UAVs is that their broader range of sizes and lighter weights allows for an equally broad range of launch options. Many MALE UAVs are launched and recovered via conventional wheeled take-off and landing, while a number of smaller UAVs can be launched using pneumatic or elastic catapults (Figure 164), and boosters. Many of these small systems can also be man-portable.

Typical Missile-related uses: UAVs described by this Item are capable of delivering a payload of less than 500 kg to a range equal to or greater than 300 km.

Other uses: Payloads can include multi-mission systems, including intelligence, surveillance and reconnaissance (ISR) equipment and conventional weapons. Smaller UAVs are more likely to be used exclusively for ISR missions and scientific research.

Appearance (as manufactured): Complete UAV systems controlled under this item are characterized by a wide variety of shapes and features. It is more common for the aircraft to have a fixed-wing and air-breathing propulsion. New versions of unmanned rotary-wing aircraft are designed to achieve ranges beyond 300 km.

Purpose built UAV systems typically exhibit a conical shape, sometimes with a bulbous area near the front end or nose of the fuselage. Complete UAV systems controlled under this item also may include manned aircraft that are modified to fly autonomously, remotely or as optionally piloted vehicles. Such systems also usually retain a cockpit, which is empty or filled with electronic equipment or payload during flight. Larger UAVs covered by 19.A.2. have several features in common with those in 1.A.2., which might include wings with large spans mounted mid-fuselage, cylindrical fuselages with pronounced bulges or domes above the nose, rear-mounted engines, V or inverted V tails, and fully retractable landing gear. Cruise missiles in this category are very similar in appearance to those in 1.A.2.

Appearance (as packaged): Category II UAVs, including cruise missiles, are manufactured in components or sections at different locations and by different manufacturers, and assembled at a military site or a civilian production facility. UAV systems described by this Item may be packaged as complete units, or they may be separated at break points and packaged using the same procedures and materials as the UAVs described in 1.A.2.



Figure 164: A medium-range endurance UAV. Despite its small size, this elastic catapult-launched UAV is capable of carrying a 1 kg payload (IR and digital cameras) to a range of 400 km. (Aerovision Vehiculos Aereos, SL)

19.A.3. Complete unmanned aerial vehicle systems, not specified in 1.A.2. or 19.A.2., having all of the following:

a. Having any of the following:

1. An autonomous flight control and navigation capability; or
2. Capability of controlled flight out of the direct vision range involving a human operator; and

b. Having any of the following:

1. Incorporating an aerosol dispensing system/mechanism with a capacity greater than 20 litres; or
2. Designed or modified to incorporate an aerosol dispensing system/mechanism with a capacity greater than 20 litres.

Note:

Item 19.A.3. does not control model aircraft, specially designed for recreational or competition purposes

Technical Notes:

1. An aerosol consists of particulate or liquids other than fuel components, by-products or additives, as part of the "payload" to be dispersed in the atmosphere. Examples of aerosols include pesticides for crop dusting and dry chemicals for cloud seeding.

2. An aerosol dispensing system/mechanism contains all those devices (mechanical, electrical, hydraulic, etc.), which are necessary for storage and dispersion of an aerosol into the atmosphere. This includes the possibility of aerosol injection into the combustion exhaust vapour and into the propeller slip stream.

Nature and Purpose: Item 19.A.3. covers UAVs equipped with or designed to carry an aerosol dispensing system/mechanism with a capacity exceeding 20 liters, and an autonomous flight control and navigation capability or the ability to sustain controlled flight beyond the line of sight of a human operator.

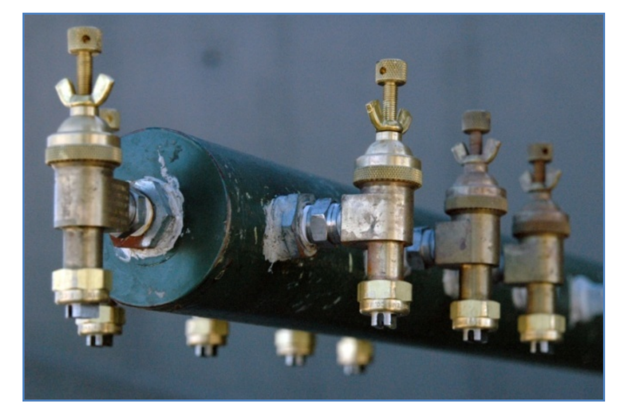


Figure 165: A Modular Aerial Spray System, used for pesticide application, can use a setting called ultra-low volume and specialized spray boom nozzles such as those shown here to spread one half to an ounce of chemical over an acre. (U.S. Air Force)

Method of operation: The UAV system can be based on an aircraft purpose-built for unmanned flight. The UAV system also can be a modification of a manned aircraft, either fixed-wing or helicopter. Depending on the means of takeoff, the aircraft can be hidden and launched from a variety of locations, including rugged airstrips, maritime vessels or standard airports. The UAV system can be controlled by an onboard navigation system, which can fly a pre-programmed route following waypoints. Alternatively, the course of the UAV system can be adjusted in-flight with commands from a ground-based system, or relayed via



an onboard data link from another platform. Meanwhile, an onboard flight control system maintains the UAV system in controlled flight, adjusting the control surfaces to maintain the system's desired flight path.

Biological warfare (BW) agents can be weaponized by conversion into aerosols. An aerosol is defined under this item as particulates or liquids other than fuel components, by-products or additives that are part of the UAV system's payload to be dispersed into the atmosphere. Such aerosols can include pesticides used to protect crops from insects and dry chemicals sprayed into the atmosphere to seed the formation of clouds. At minimum, a spray system contains a tank to store the aerosols, a pump to flow the aerosols to the spray nozzle and the nozzle itself to emit the aerosol cloud. (Figure 165)

Typical missile related uses: The dispersal of BW or chemical agent using an aerosolized cloud is the most effective means of dissemination.

UAV flight trajectories, including those of cruise missiles, are suitable for dispensing biological and chemical agents, as the missile can be preprogrammed to fly over a selected target and dispense the agents from the warhead bay over a period of time from a low altitude.

Other uses: A UAV described in this Item could be used in agricultural and pest control industries.

Appearance (as manufactured): UAVs incorporating aerosol dispenser(s) or modified to be able to carry such systems/mechanisms take a variety of forms. Range and payload capacities vary, and they can be either fixed-wing or rotary-wing. Complete UAV systems controlled under this item may also include manned aircraft that are modified to fly autonomously or remotely. Such modified aircraft also usually retain a cockpit, which is empty or filled with electronic equipment or payload during flight.

The majority of known systems for conducting autonomous aerial spraying are helicopter-based. These vertical take-off and landing (VTOL) UAVs are usually designed for agricultural purposes, spraying crops with pesticides or fertilizer. Systems in this category are often characterized by having one or more payload tanks externally mounted, either on the belly or on the sides of the aircraft; and spraybars and/or a cone nozzle. These aircraft can also be fitted with observational payloads, including TV and IR cameras and other sensors. Rotary-wing UAVs designed for agricultural spraying, such as that depicted in Figure 166, tend to have a reduced mission radius, range, and endurance, due to command and control limitations and intended mission of the aircraft, which stipulates proximity spraying. Typically they cannot

operate for more than a few hours and at distances further than a couple of miles, however longer-range designs are possible in this category.

Aerosol delivery UAVs on fixed wing platforms could be designed as either UAVs fitted with tanks and dispersion devices, or as aircraft designed for piloted spraying purposes outfitted with autonomous control systems. These could have either internal or external tanks, and spraying systems mounted to the belly, nose, tail, or wings of the craft.



Figure 166: A rotary-wing UAV designed with chemical tanks and spraybars for agricultural purposes. (Yamaha)

Appearance (as packaged): UAV systems controlled under this Item may be packaged for shipment as described in Item 1.A.2. These UAVs are often packaged as several separate components and subsystems, and assembled together when needed for operation. The subsystems could include avionics, data links, ground station and a launch and recovery system. Components could include elements of the fuselage, wings, control surfaces and landing gear. Some UAV systems also incorporate skids for landing, with catapults used as the launching mechanism. Tankage and spray apparatus may be packed in wooden crates and shipped separately.

19.B. Test and Production Equipment

19.B.1. "Production facilities" specially designed for systems specificed in 19.A.1. or 19.A.2.

Nature and Purpose: Production facilities that are specially designed for the construction of complete delivery systems take a variety of forms. Some are integrated into a larger industrial complex that includes design and testing capabilities while others stand-alone away from populated areas. Both contain all of the necessary jigs, fixtures and related tooling to produce rocket or UAV systems. Facilities for ballistic missiles and space launch vehicles require at least one building large enough to assemble the entire system and contain the necessary alignment fixtures and material handling equipment to accomplish the mission. UAV facilities may be considerably smaller and resemble normal warehouses or industrial sites.

Method of Operation: Materials, components and sub-assemblies are delivered to the production facility in boxes, crates and, for larger items, on pallets, trucks or railcars. For rocket systems, this includes fuel and oxidizer tanks or motor cases, engine assemblies, skins and payload. For UAV systems, this includes the airframe, wing spars, and engine assemblies. Material handling equipment such as forklifts and overhead cranes are used to move the items to their proper position in the production facility. Jigs, fixtures, alignment equipment and tooling are then used to build the missile or UAV system. For large missile or space launch vehicles, alignment lasers are used to assist the process.

Typical Missile-Related Uses: Production facilities are used to assemble a complete missile system from its subassemblies and component parts. At the end of each production step, mechanical and electrical fit and function tests are performed to verify that the assembly is ready for the next step. After a rocket is assembled and passes all production tests, it may be disassembled at prescribed body break points. These separated missile components are loaded into individual containers or crates for shipment to a facility for long-term storage or to the operational launch point for final reassembly and use. However, UAVs, including cruise missiles, are typically shipped fully assembled to operational units (depending on the type of launch platform) or to storage depots for long-term storage.

Other Uses: The jigs, fixtures and tooling are typically designed for a single rocket or UAV system. Modifying these units for other uses is not practical or economical.

Appearance (as manufactured): Jigs and fixtures are usually assembled by welding or bolting large steel plates and I-beams or tubular members together on the floor of the production building. In some cases, these fixtures are built on floating pads, not bolted to the floor; such pads isolate the structure from vibrations, which might otherwise cause misalignment of their precision reference points.

Appearance (as packaged): Assembly jigs and fixtures for some systems are often too large and heavy to be packaged and shipped to the production plant as complete units. Instead, component parts are shipped separately in large crates or protected on pallets for assembly onsite. They will be securely fastened to the crate to restrain motion and prevent damage. Smaller jigs may be individually packaged on crates or

pallets for shipment. Large factories may produce assembly jigs and fixtures on-site as part of their overall manufacturing effort.

19.C. Materials

None.

19.D. Software

19.D.1. "Software" which coordinates the function of more than one subsystem, specially designed or modified for "use" in the systems specified in 19.A.1. or 19.A.2.

Note:
For a manned aircraft converted to operate as an unmanned aerial vehicle specified in 19.A.2., Item 19.D.1. includes "software", as follows:
a. "Software" specially designed or modified to integrate the conversion equipment with the aircraft system functions;
b. "Software" specially designed or modified to operate the aircraft as an unmanned aerial vehicle.

Nature and Purpose: The software described in this Item has the same nature and purpose as that described in Item 1.D.2.

Method of Operation: The software described in this Item has the same method of operation as that described in Item 1.D.2.

Typical Missile-Related Uses: The software described in this Item has the same missile-related uses as the software described in Item 1.D.2.

Other Uses: N/A

Appearance (as manufactured): The software described in this Item has the same appearance as that described in Item 1.D.2.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, compact discs, USB flash drives and documents containing software that controls more than one subsystem and that is specially designed or modified for use in systems specified in 19.A. are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software and documentation can be transmitted over a computer network or the internet.

Additional Information: Typically, there would be no flight software in small rocket systems which are unguided, spin-stabilized, "point and shoot" systems. A two-dimensional/three degree-of-freedom trajectory simulation code might be loaded into the launch console or might be used to prepare firing tables.

19.E. Technology

19.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment specified in 19.A.1. or 19.A.2.

Nature and Purpose: The technology described in this Item has the same nature and purpose as the technology described in Item 1.E.1.

Method of Operation: The technology described in this Item has the same method of operation as the technology described in Item 1.E.1.

Typical Missile-Related Uses: The technology described in this Item has the same typical missile-related uses as the technology described in Item 1.E.1.

Other Uses: N/A

Appearance (as manufactured): N/A

Appearance (as packaged): N/A

Category II - Item 20

Other Complete Subsystems

Category II – Item 20: Other Complete Subsystems

20.A. Equipment, Assemblies and Components

20.A.1. Complete subsystems as follows:
a. Individual rocket stages, not specified in 2.A.1., usable in systems specified in 19.A.;
b. Rocket propulsion subsystems, not specified in 2.A.1., usable in the systems specified in 19.A.1., as follows:
1. Solid propellant rocket motors or hybrid rocket motors having a total impulse capacity equal to or greater than 8.41×10^5 Ns, but less than 1.1×10^6 Ns;
2. Liquid propellant rocket engines or gel propellant rocket motors integrated, or designed or modified to be integrated, into a liquid propellant or gel propellant propulsion system which has a total impulse capacity equal to or greater than 8.41×10^5 Ns, but less than 1.1×10^6 Ns.

- Brazil
- China
- Egypt
- France
- Germany
- India
- Iran
- Israel
- Italy
- Japan
- North Korea
- Pakistan
- Republic of Korea
- Ukraine
- United Kingdom
- United States

Global production



Nature and Purpose: Complete subsystems (including solid, liquid, hybrid or gel propellant rocket stages, solid, hybrid, or gel propellant rocket motors, and liquid rocket engines) used in systems falling under Item 19.A.1. are similar in most respects to those items controlled by Item 2.A.1. The key difference is determined by the absence of a requirement to have a payload carrying capability of 500 kg or more in the systems controlled by Item 19.A. The smaller size of these systems dictates that their subsystem components and propulsion systems are likewise smaller in size and less powerful than those controlled by Item 2.A.1.

Solid, hybrid and gel propellant rocket motors that meet the requirements of Item 20.A.1. but not Item 2.A.1. are relatively unusual, because the total impulse thresholds for this control criterion are close together. The Item 20.A.1.b.1. threshold exceeds three quarters of the Item 2.A.1.c.1. amount.

Liquid propellant rocket engines have been built in a very wide range of sizes (thrust magnitudes). They range from large space launch engines to small reaction control engines designed to adjust a space vehicle's trajectory outside of the atmosphere. While these small reaction control engines operate at low thrust, they typically are capable of long burn durations (thousands of seconds), and consequently they too can achieve the total impulse control criterion specified by Item 20.A.1.b.2. In practice, the total

impulse capacity of any liquid rocket engine is determined by the volume of the propellant tanks connected to the engine.

Small rocket stages, along with their solid motors or liquid engines, have been receiving increased attention in the twenty-first Century for the purpose of delivering the smallest satellites to earth orbit. Solid rocket motors are sometimes used for spacecraft maneuvers beyond low earth orbit.

Method of operation: Rocket stages generally consist of a structure, solid or liquid propulsion, and a control system. As with their larger equivalents, multi-stage rocket systems discard lower stages as they burn up their propellant. For details of methods of operation, see the corresponding explanations in the MTCR Handbook for Items 2.A.1.a. and 2.A.1.c.

Typical Missile-Related Uses: Rocket stages controlled by Item 20.A.1. are necessary and vital subsystems of the rocket systems of which they are a part. They are also used in missile testing and development. Solid, hybrid and gel propellant rocket motors and liquid propellant engines provide the thrust to accelerate the system to the required velocity.

Other Uses: In test facilities, relatively small solid rocket motors have been used to achieve high accelerations and high speeds, in particular to push rocket sleds that accelerate a test object on a track along the ground. Small liquid rocket engines are widely used on satellites and spacecraft.

Appearance (as manufactured): Rocket stages, solid, hybrid and gel propellant motors, and liquid engines controlled by Item 20.A.1. look like smaller versions of their larger counterparts controlled by Item 2.A.1. Individual rocket stages controlled by Item 20.A.1. would generally be shaped as cylinders ranging from 1.5 m to 3 m in length and 0.3 m to 1 m in diameter. Solid rocket stages and motors typically are cylinders manufactured from robust sheet steel, composite materials (fibers in resins), or a combination of both. Liquid rocket stages are cylinders consisting mostly of the walls of propellant tanks, the latter typically made of aluminum.

Solid propellant rocket motors are cylindrical tubes with domes at both ends for attachment of the igniter and nozzle, respectively (Figure 167). Nozzles are usually attached prior to shipment. The size and dimensions of these motors depends on their purpose. Solid rocket motors shown in Figure 168 have a diameter of 0.7 m and a length of 1.2 m. Their nearly spherical case shape makes them appropriate for maneuvers beyond most of the atmosphere, including missile upper stages as well as spacecraft maneuvering.

Liquid rocket engines for relatively small missiles are less likely than their larger counterparts to include turbine-driven rotating centrifugal pumps (turbopumps). Figure 167 shows an example of such a pressure-fed engine, designed to receive propellants from tanks that are pressurized to higher levels than the engine combustion chamber.

Appearance (as packaged): Rocket stages are shipped in purpose-built steel or wooden containers or crates. Solid rocket motors are usually shipped in steel or aluminium containers or wooden crates. Liquid

rocket engines also are shipped in specially designed containers or crates.

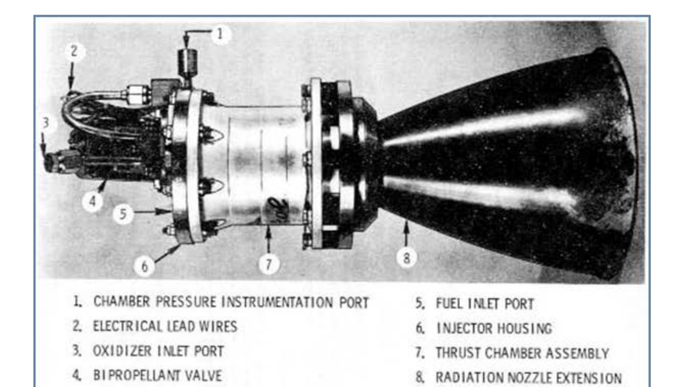
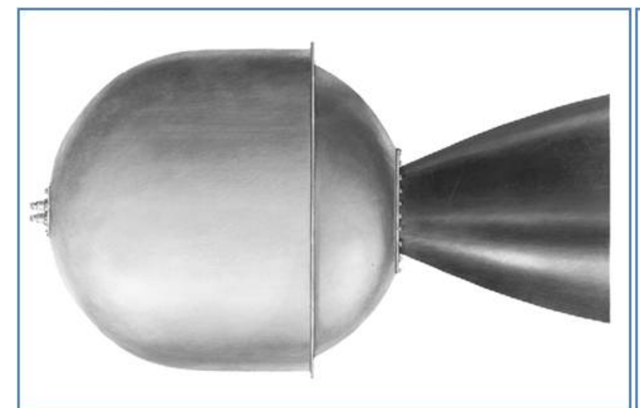


Figure 167: *Left*: A reaction control engine; *Bottom left*: a stack of solid propellant rocket motors controlled under Category II. Motors on the left of that photo are large enough to be controlled under Item 2, Category I. *Below*: A side view of a shipping container containing four Category II solid propellant rocket motors. (MTCR Equipment, Software, and Technology Annex Handbook, Third Edition (May 2005))







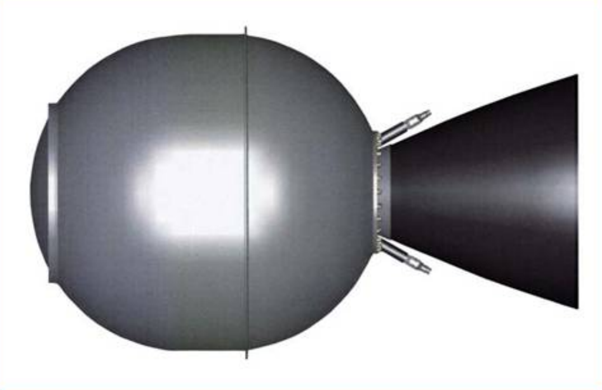


Figure 168: On the left is a category II rocket motor which has been used as the apogee kick motor in a range of applications since 1975. On the right is a version of the same motor developed in 2006. (ATK)

20.B. Test and Production Equipment

20.B.1. "Production facilities" specially designed for the subsystems specified in 20.A.

Nature and Purpose: Subsystem production facilities are often large industrial areas designed to manufacture solid propellant rocket motors or liquid propellant rocket engines. Solid propellant mixing facilities are often built in isolated regions, removed from populated areas for both security and safety.

Method of Operation: Subassemblies are manufactured and often tested in their production facilities before they are shipped either to storage or to a final assembly area. Raw materials such as sheet steel are rolled into the proper forms and welded together to form cylinders that will become the solid propellant rocket motor case. End domes are welded onto these cylinders to complete the enclosure. Each end dome has a reinforced circular opening to mount the stage igniter and to attach the nozzle.

Liquid propellant rocket engines or gel propellant rocket motors are complex mechanical devices that require many precise machining and assembly steps, often in clean rooms. Small precision parts are cast, machined, cleaned and assembled.

Typical Missile-Related Uses: The components and assemblies manufactured at these facilities are used to build and test items listed in Item 20.A.

Other Uses: N/A

Appearance (as manufactured): Item 20.B.1. production facilities and equipment for the complete stages and solid, hybrid and gel propellant rocket motors and liquid propellant rocket engines are similar to those described in Item 2.B.1. The facilities and equipment described in this Item may be indistinguishable from those designed to produce larger rocket stages or liquid propellant rocket engines. However, they may be smaller in size. Production facilities and equipment for individual rocket stages and motors controlled by Item 20.A.1. are similar to those discussed in Item 2.A.1., and in most cases will be indistinguishable from those for larger items.

Appearance (as packaged): The facilities and equipment described in this Item may be packaged using the same procedures and materials as those described in Item 2.B.1. for the complete stages and solid, hybrid or gel propellant rocket motors and liquid propellant rocket engines.

20.B.2. "Production equipment" specially designed for the subsystems specified in 20.A.

Nature and Purpose: Production of these subsystems requires equipment tailored to the specific type of subassembly. Each subsystem production facility must contain specialized equipment, jigs, fixtures, molds, dies and mandrels that are used to manufacture the subassembly's components, assemble them and test the subassembly.

Method of Operation: Equipment used to build solid propellant rocket motors includes metalworking machinery, tools for grinding, filtering and mixing propellant, molds or mandrels to form the motor core or burning surface, devices for fabricating and pyrolizing motor nozzles and equipment to test the thrust vector control system on the completed motor. Facilities may also contain winding equipment for covering motor cases with composite fiber materials.

Every component in a liquid propellant rocket propulsion subsystem requires production equipment. Propellant on-off valves require milling machines to manufacture metal parts and flow and leak testing equipment for quality control. Electro-discharge machining (EDM) is used extensively in the manufacture of injectors for liquid propellant rocket engines. When first developed, the process was controlled by setup fixtures and manual controls. Computer-controlled EDM and CAD/CAM links are now the norm.

Typical Missile-Related Uses: The components and assemblies produced using the equipment described in this Item are used to build and test items listed in Item 20.A.

Other Uses: N/A

Appearance (as manufactured): Item 20.B.2. "production equipment" is similar to the equipment for the complete stages and solid, hybrid or gel propellant rocket motors and liquid propellant rocket engines described in Item 2.B.2. The equipment described in this Item may be indistinguishable from that designed to produce larger rocket stages or liquid propellant rocket engines. However, it may be smaller in size.

Appearance (as packaged): The "production equipment" described in this Item may be packaged using the same procedures and materials as those described in Item 2.B.2. for the complete stages and solid, hybrid or gel propellant rocket motors and liquid propellant rocket engines.

20.C. Materials

None.

20.D. Software

20.D.1. "Software" specially designed or modified for the systems specified in 20.B.1.

Nature and Purpose: Automated and computer-assisted manufacturing procedures, including numeric control, are increasingly used to produce missile components rapidly, accurately and with a high degree of repeatability. These procedures require specifically designed software.

Method of Operation: Modern machine tools are computer numerically controlled (CNC). A microprocessor in each machine reads the G-Code program that the user creates; it then performs the programmed operations. Personal computers are used to design the parts and are also used to write programs either by manual entry of G-Code or by use of computer-aided manufacturing (CAM) software that creates G-Code from the user's input of cutters and toolpath.

Typical Missile-Related Uses: CNC equipment is widely used in the manufacturing and testing of missile system parts and relies on both internal software and CAM software to create the various parts of missile systems. CNC equipment controls and manages both the flow-forming process used in steel motor case production facilities and the filament-winding machines that lay epoxy– or polyester-resin-coated fibers onto rotating mandrels to create composite motor cases. CNC lathes and milling machines can be used to turn the specialized graphite or carbon billets into solid propellant motor nozzles.

Other Uses: Software that is used to operate equipment that manufactures subassemblies may also be employed, with modifications, to control products manufactured in the civil and military aviation industries.

Appearance (as manufactured): Typically, this software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media—including magnetic tape, floppy disks, removable hard disks, USB flash drives, compact discs and documents—can contain this software and data.

Appearance (as packaged): Magnetic tape, floppy disks, removable hard disks, USB flash drives, compact discs and documents containing missile production control software are indistinguishable from any other storage media. Only labeling and accompanying documentation can indicate its use unless the software is run on the appropriate computer. This software, including the documentation, can be transmitted over a computer network.

20.D.2. "Software", not specified in 2.D.2., specially designed or modified for the "use" of rocket motors or engines specified in 20.A.1.b.

Nature and Purpose: The “software” described in this Item has the same nature and purpose as that described in Item 2.D.2.

Method of Operation: The “software” described in this Item employs the same method of operation as that described in Item 2.D.2.

Typical Missile-Related Uses: The “software” described in this Item has the same missile-related uses as the software described in Item 2.D.2.

Other Uses: N/A

Appearance (as manufactured): Typically this software takes the form of a computer program stored on printed, magnetic, optical or other media. Any common media – including magnetic tape, floppy disks, removable hard disks, USB flash drive, compact discs and documents – can contain this software and data.

Appearance (as packaged): The “software” described in this Item has the same packaging appearance as that described in Item 2.D.2, and can be transferred over the internet.

20.E. Technology

20.E.1. "Technology", in accordance with the General Technology Note, for the "development", "production" or "use" of equipment or "software" specified in 20.A., 20.B. or 20.D.

Nature and Purpose: Technology controlled under Item 20.E.1. covers the instructions and knowledge needed to develop, produce or use any of the equipment or software specified in Items 20.A., 20.B. or 20.D.

Method of Operation: Technical assistance is available in many forms. Technical assistance may consist of instruction provided by a person experienced in one or more controlled subjects (such as liquid propellant rocket engines) who acts as a trainer in a classroom on or near the production site. A country may receive technical assistance from one or more consulting services who specialize in a controlled process or who assist in procuring components or materials that are difficult to obtain. Additionally, a country may receive technical assistance by sending students to other countries that possess the required technology so they may learn and practice the skills necessary to build the required systems. Any manuals and materials received during training may qualify as technical data.

Typical Missile-Related Uses: With limited exceptions, technical assistance required to build missile subassemblies is used only for that purpose.

Other Uses: N/A

Appearance (as manufactured): N/A

Appearance (as packaged): N/A

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